CPE Comments and Topics

From crucible to reactor

BRITAIN'S industrial revolution in the middle of the 18th century was born out of her need to expand the only major industry at that time, the textile industry. Large-scale production could only be effected by some form of mechanisation of which Arkwright's water-frame and Hargreaves' spinning-jenny were the first rudimentary attempts. However, without some cheap and unlimited source of power, mechanisation would have been doomed to failure. By one of those coincidences which abound in history, the steam engine, developed by Watt during the same period and only up to then applied to the locomotive, was suitably adapted to drive the early textile machines.

The origins of the chemical industry go back to the same period of the 18th century. The early chemical manufacturer considered himself a practical man and had very little contact with the men of science who were then busily propounding new theories that finally established chemistry as a scientific discipline, divorced from the stultifying influence of alchemy.

A milestone in the history of the 18th-century chemical industry was the development of a process for manufacture of artificial soda by Nicolas Leblanc. Leblanc was a product of the first French school for engineers, the Ecole Polytechnique, which had been created specifically to train young men in the arts and science of manufacture. Due to the exigencies of the Napoleonic wars, Leblanc's soda process was first adapted on a large scale in Britain. However, the main drawback to the process was that it produced one material, soda, and consumed two valuable others, sulphuric and hydrochloric acid. In the early years no by-products were obtained from this rather complicated reaction, due mainly to the manufacturers who were not interested in the technology of chemical processing. Nevertheless, some far-sighted men, employed by these manufacturers as chemists but with little academic background, did attempt some rudimentary improvements. One such innovator was William Gossage who, in 1836, designed the first packed column for condensation of acid fumes evolved in the saltcake stage of the process. Walter Weldon and Henry Deacon were separately involved in developing processes to recover the valuable chlorine from waste hydrochloric acid by means of manganese dioxide. Such improvements were usually arrived at quite empirically. For this reason, although Gossage, Deacon and others had been continuously interested in the ammonia soda process which was more compact and less wasteful, they were unable to design such a plant simply because they did not have the necessary engineering training. Thus during the early and middle 19th century the gulf between science and industry was so wide that few believed it could ever be bridged.

When the first continuous process for production of ammonia-soda was eventually developed by the Belgian, Albert Solvay, Ludwig Mond a young German chemist working in England, realised its enormous potentialities and obtained a licence for its application in this country. This first true chemical-engineering process was established in Britain in 1883 and marked the beginning of the end of the cumbersome, wasteful *Leblanc* process.

Very soon the significant reductions in the price of *Solvay* soda compared with *Leblanc* soda was sufficient proof of its success and this was a challenge to British chemists to improve the technology and design of existing plant. Thus they had to become acquainted with the new hybrid science, physical chemistry as well as with mechanical engineering which had only recently become an exact applied discipline. Very slowly and very painfully chemical engineering was born in the last decades of the 19th century. It set out to form the missing link between the manufacturer, chemist and mechanical engineer and to create an industry which was both scientifically designed and managed—to raise it from the age of the crucible to that of the reactor.

New venture in cost engineering

COSTING of chemical plant is one of the most thankless and cumbersome tasks confronting chemical engineers in this country. The reason for this is not because it is in any way more difficult than other facets involved in plant design and construction but only due to the dearth of any published, up-to-date information relating to current costs of plant and equipment. Whereas in the United States several technical journals publish such information regularly as a matter of course, in this country any such venture is well-nigh impossible because of the reluctance of manufacturers to reveal this information. The recent establishment of a British Group of the American Association of Cost Engineers must, therefore, be greeted with whole-hearted approval.

The objectives of this group are:

1. To advance the science and art of cost engineering.
2. To provide forums and media through which experience with the principles and techniques of cost engineering may be reported, discussed and published for the common good.
3. To promote standardisation of terminology in cost engineering and, so far as is practicable, develop standard methods.
4. To encourage instruction in cost engineering in standard engineering curricula.
5. To co-operate with other organisations having common interests.

An important function of the A.A.C.E. in the U.S. is

the collection and dissemination of cost data and the development of improved methods for accurately and rapidly making estimates of capital costs. The association has published a cost index manual giving the principle applications and limitations of various cost indices and is also investigating the feasibility of an index of relative cost in various locations. It is to be hoped that the establishment of this group will be the first step towards establishing cost engineering as an applied science which can usefully be taught as a separate branch in the general engineering curricula.

Gas centrifuge: fact or fiction?

SEVERAL weeks ago we witnessed a furore in the British Press concerning the new gas centrifuge-technique for separating uranium isotopes. It was claimed that a German firm had fully developed such a technique for separation of U^{235} and that gas centrifuges were already being manufactured and exported to underdeveloped countries who, as a result, were now in the position to apply this in weapons manufacture—the era of the home-made atom bomb was just around the corner!

It must always be regretted when reports of technical matters are distorted and sensationalised; not least in a subject which affects the survival of every human being. The true facts of this story are as follows. Gas centrifuging is one of the methods of separating uranium isotopes and has been continuously investigated by the Americans, British and Germans since the end of the war. Whilst the Americans and British concentrated on the more practicable gas-diffusion process, which uses an enormous amount of electricity, the Germans (who had no nuclear industry after the war) carried on investigating the gas centrifuge. As a result some considerable insight into this technique was gained by them and several patents were taken out for a prototype gas-centrifuge model.

Mr. John McCone, chairman of the U.S. Atomic Energy Commission, made the following statement concerning the prospects of this gas centrifuge: 'After careful study and discussion with many qualified scientists about the gas-centrifuge process, it is my conclusion that practical use of this method by any nation for producing weapons material is several years away. There is an enormous amount of development work still to be done. We foresee that the gas-centrifuge ultimately can be used to separate U^{235} from U^{238} in order to produce weapons-grade materials. But this cannot be done satisfactorily with present technology. We do not think that the problems that remain are insoluble, but they certainly will take time to solve. The process will not be simple or cheap. Apparently, as we see the trend of future development, it will take thousands of gas-centrifuge machines to produce materials for weapons '.

It is clear from this that there was very little fire behind the massive smoke-screen of publicity made for gas centrifuging. Sensationalism in nuclear technology is a dangerous game and is much to be deprecated.

H_2S removal from gases

A NEW process called the *Stretford Process* for extracting hydrogen sulphide and recovering pure sulphur from coal gas, petroleum gases and other gases, by the use of certain reagents produced in the manufacture of anthraquinone dyes from coal tar, was recently developed by a team of North Western Gas Board technologists and the research department of the Clayton Aniline Co. The conventional system for removing hydrogen sulphide from coal gas uses powdered iron oxide through which the gas is passed. It is a cumbersome system and not without danger, especially when the cast-iron boxes holding the saturated oxide are emptied. The removal of hydrogen sulphide by this process costs about 0.3 penny therm.

The *Stretford Process* consists of washing the gas to be purified with a mixture of the sodium salts, dissolved in water, of two special forms of anthraquinone di-sulphonic acids. These are the ' 2—6 ' and ' 2—7 ' forms whose molecular structure gives them a specially speedy reactivity. The process is cyclic, continuous and automatic, the liquid reagents being regenerated in the course of the cycle as the sulphur is filtered out in finely divided form. The cost of purification has been about 0.2 penny/therm, according to the market price obtained for the recovered sulphur.

There are four steps in the purification cycle:

(1) The gas passes upwards through a washing chamber meeting the anthraquinone di-sulphonic sodium salt solution injected as a spray at the top of the chamber, as it drips downward in a film over the washing grids. In this step the solution removes the hydrogen sulphide from the gas. The gas passes out of the washer at the top ready for use.

(2) The solution carrying the hydrogen sulphide with it passes into a reaction tank where it is allowed to stay for sufficient time to permit the hydrogen sulphide to react with the carbonyl radicles of the solution to produce free sulphur.

(3) The solution is pumped from the reaction tank into an oxidation tower through injectors which entrain sufficient air to convert the hydroquinone back to the original quinone, ready for another cycle.

(4) Before the solution, now holding free sulphur, is passed back into the washer to complete a fresh cycle, it is passed through a continuous rotary vacuum filter which removes the sulphur from it.

Further applications of this process are in removal of hydrogen sulphide from the gases now blown to waste in the oilfields, and in treatment of waste gases at oil refineries and tail gases sold to the chemical and gas industries. In the rayon (viscose) and transparent paper industry removal of hydrogen sulphide and carbon bi-sulphide from the air will result in a cheapening of the whole manufacture by preventing the degradation of the active carbon used—proving the versatility of this process.

Fluorine—difficulty in handling

THE requirements of rocket designers for efficient propellant systems has increased the engineer's interest in the fluorine-hydrogen system. Some general properties of fluorine and particularly corrosion behaviour of metals exposed to it were discussed in a paper published in the proceedings of the Propellant Thermodynamics and Handling Conference, by E. L. White and F. W. Fink. The paper states that the importance of fluorine as the oxidiser for conventional rocket fuels is due to the fact that the specific impulse of fluorine oxidiser systems is higher than that of oxygen or nitric acid oxidiser systems. In addition, a saving in volume is achieved due to the high density of liquid fluorine. Unfortunately, the advantages in using fluorine are offset by serious problems associated with its toxicity, low boiling point and high reactivity leading to difficulty in handling.

There is considerable information on the corrosion behaviour of materials exposed to fluorine—no material is completely inert to attack by this extremely active element. Nevertheless, many of the common construction materials, when used in the established temperature ranges, can be expected to give acceptable service. Nickel alloys can be used up to 1,200°F.; aluminium and magnesium to 900°F.; copper and possibly thorium, to 700°F.; pure iron to 600°F.; mild steels with low silicon content to 400°F.; and titanium and zirconium to 300°F. Chromium plate is useful up to at least 400°F. and nickel plate up to higher temperatures. The use of tantalum, tin, silver, lead and platinum is possible at room temperatures. Silicon, vanadium, rhenium and uranium are attacked even below room temperature. Liquid fluorine at liquid nitrogen temperatures is more corrosive than the gas at room temperature.

The metals which can be used with liquid fluorine are nickel and nickel alloys, stainless steels, aluminium, magnesium, mild steel, titanium, tantalum and zirconium. Except for very special applications, the only organic materials which can be used with either liquid or gaseous fluorine are the fluorocarbons —polytetrafluoroethylene is the best of these materials. Of the non-metallic inorganic materials, alumina is the most resistant.

Fischer-Tropsch vs. Kolbel-Engelhard

PROF. KOLBEL, co-discoverer of the Kolbel-Engelhard synthesis, has made the following comments concerning our recent criticism of the Wilson Committee report ' Oil-from-coal, another agonising reappraisal? ' which we published in October (CPE, p. 433).

' By using a gas composed of carbon monoxide and hydrogen, hydrocarbons can be made relatively cheaply by means of the Kolbel-Engelhard synthesis mainly because the expensive gasification process, which represents about 80% of the total costs in the classical Fischer-Tropsch process, is obviated. It is most important that this synthesis should not produce hydrocarbon fuels which are fairly cheap nowadays, but rather hydrocarbons suitable for chemical or petrochemical reactions. Petroleum hydrocarbons which are completely unbranched can only be branched with great difficulty, whereas such cross-linking is quite unnecessary for synthetic hydrocarbons which are already cross-linked to some extent. For many technical reactions solvents are required without any traces of sulphur, *e.g.* in Ziegler chemistry. Other than by synthesis, such pure hydrocarbons could not be obtained. Moreover, the high prices which are nowadays paid for hard waxes and table paraffins would make a synthetic process with its greater flexibility far more economical '.

The Kolbel-Engelhard synthesis, which is actively developed in Germany at present, will be described fully in a special article by Prof. Kolbel in next month's issue. Due to the different catalysts that can be used in this synthesis a wider spectrum of hydrocarbons is attainable. It seems to be commonly accepted everywhere that there is no economic future in synthesising hydrocarbon fuels—the world market price is so low for petroleum that no synthetic reaction could compete. However, there is a strong case to be made out for synthesising other types of hydrocarbons. Could not a project comparing Kolbel-Engelhard and Fischer-Tropsch syntheses for hydrocarbon products be suitably allocated to the Warren Springs Laboratory which, until the Wilson Committee report, was actively engaged in Fischer-Tropsch fuel synthesis? A costly pilot plant for this purpose already exists at Warren Springs and might have to be completely scrapped in the near future. This would be not only a fearful waste of money but also of know-how, because many of the staff at Warren Springs have been actively engaged in Fischer-Tropsch work for over 20 years.

Acid deposition in oil-fired boilers

THE principal difficulties associated with burning fuel oil in power stations were recently described in a paper presented at the Institute of Fuel by P. A. Alexander and others from the Central Electricity Research Laboratories. These difficulties include:

(1) blockage of air-heater;
(2) corrosion of air-heater, ducts and dust-collection plant;
(3) emission of acid-laden smuts from the stack.

These are all caused by condensation of sulphuric acid from the flue gas on to cool surfaces. The preferred method of reducing such condensation has been neutralisation of the acid by the injection of basic substances before the flue gas meets a cool surface. Such additives include finely powdered solids, sprayed liquids and ammonia gas.

It was decided in January, 1958, to conduct trials to determine the most promising additives at one particular power station under strictly comparable conditions. Eventually the trials were conducted at Bromborough and Ince power stations; the Bromborough boilers were equipped with steam atomising burners whereas the Ince boilers had pressure atomising burners. To ensure optimum distribution of the

powders in the flue gas and to provide the maximum period of contact, additives were injected into the combustion chamber. Observations could then be made of their relative tendencies to foul the furnace and superheater. Trials without additive were essential at both Bromborough and Ince to determine the properties of flue gas in each boiler.

Despite difficulties due to factors inherent in the plant and equipment and unpredictable changes in the fuel supplied, comparable tests were made of five additives. As a result of these tests the following recommendations were suggested:

1. That short-term methods of test should include the measurement of the acid-deposition rate and the determination of sulphur oxides.
2. All oil-fired boilers should be operated with the minimum practicable amount of excess air to suppress SO_3 formation.
3. Magnesium carbonate and zinc should both be considered in future trials of additives. Injection of pulverised fuel-ash could yield a dry air-heater deposit but would be practicable only at low SO_3 concentrations.
4. More work should be carried out to determine the dependence of SO_3 formation on the sulphur content of the fuel.
5. Research should be carried out on the role of economiser and air-heater deposits in the oxidation of SO_2.

These recommendations indicate quite clearly that fouling of power plant could be avoided if only a little more planned research into the causes were carried out systematically.

Challenge to chemical engineers?

THE theoretical basis of heat transfer applied to the design and operation of heat exchangers is quite terrifying to many engineers. There is, admittedly, an enormous difference between the design engineer who calculates the heat capacity for a certain exchanger and the plant engineer who actually uses such an exchanger to pre-heat x gal./hr. liquid by cooling y cu.ft./hr. gases. The former tries to apply physical theory to design practical plant, whereas the latter must work empirically with the plant as best he can. Yet must not both learn from one another?

Boilers and condensers have been used for well over a century and the rudiments of heat-transfer theory were already propounded at the end of the 19th century by Nusselt and his assistants. These pioneers were physicists who applied classical physical theory to mechanical engineering; as a result of their work an insight was gained into the mechanism of heat transfer.

Chemical engineers, after they first became acquainted with this subject, applied its principles not only to the gas-steam media, for which mechanical engineers had applied them, but for all fluids which are heated or cooled in the course of a chemical process. The concept of mass transfer, in which matter is transferred rather than heat, was soon propounded; its philosophical connections with heat transfer are obvious. The principles of mass transfer are simply that the amount of mass transferred is proportional to a transfer coefficient $\times$ the driving force, which is the pressure difference between the two media (similar to the heat transferred being proportional to the transfer coefficient $\times$ the driving force, the temperature difference).

This month's special feature on heat exchangers clearly illustrates that heat transfer design has developed enormously since its early days mainly because of the modern demand for special-purpose exchangers in nuclear power stations. Transient heat transfer is now being examined more closely, as F. L. Carvalho's article shows, with the result that many assumptions made previously in connection with steady state conditions are no longer found to be tenable.

The similarity between heat and mass transfer and its application for design of various chemical plant is described in another article by Dr. F. Molyneux. How long will it be now before unsteady state mass transfer is rigorously studied and applied in design of distillation columns, evaporators and extractors?

How good is your memory?

DO you remember the good old days? We are indebted to *Albright News* and the Canadian magazine *Municipal World* for the following gem about early Canadian life:

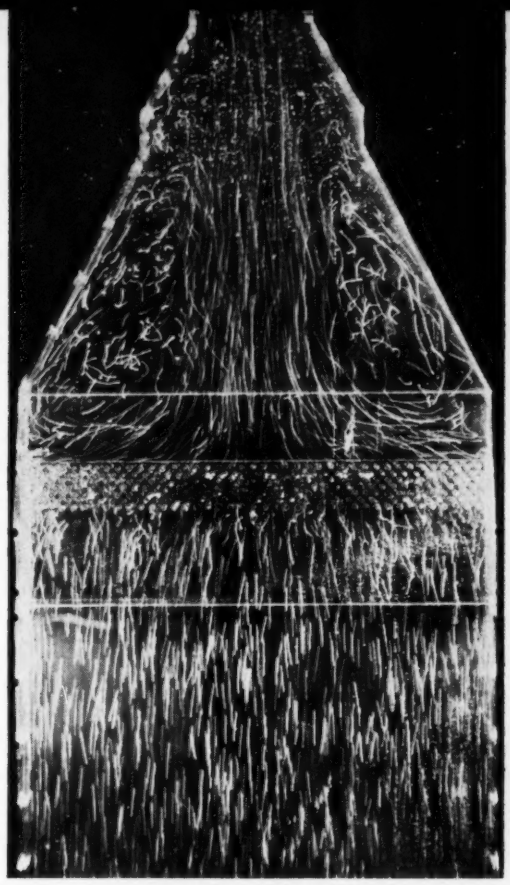
'In an age when coffee breaks, the five-day week, air conditioning and other amenities are taken for granted it's enlightening to read the Office Rules drawn up by one employer of the 1870s.

1. Employees will daily sweep floors, dust the furniture and shelves.
2. Each day, fill lamps, clean chimneys and trim wicks. Wash windows once a week.
3. Each clerk will bring in a bucket of water and a scuttle of coal for the day's business.
4. Make your pens carefully; you may whittle nibs to your individual taste.
5. The office will be open at 7 a.m. and close at 8 p.m. daily, except on the Sabbath on which day it will remain closed. Each employee is expected to spend the Sabbath by attending church and contributing liberally to the cause of the Lord.
6. Men employees will be given an evening off each week for courting purposes or two evenings a week if they go regularly to church.
7. After an employee has spent his hours of labour in the office, he should spend the time reading the Bible and other good books.
8. Any employee who smokes Spanish cigars, uses liquor in any form, gets shaved in a barber shop or frequents pool and public halls, will give me good reason to suspect his worth, intentions, integrity and honesty.
9. The employee who has performed his labours faithfully, and without fault for a period of five years, and who has been thrifty and attentive to his religious duties will be given an increase of 5 cents per day, provided a just return in profits from the business permits it'.

Design of Heat Exchangers for Nuclear Power Plants

By B. F. Ridal,* B.Sc.Tech., A.M.Inst.F.

and J. H. Wilson,* B.Sc.



Flow pattern at inlet to s.r.u.

Since the formation of the nuclear power consortia in 1955 a number of developments in heat exchangers have resulted in considerable economies both in capital and generation costs. Some factors affecting mechanical design, such as gas velocities and by-passing of finned sections, are discussed in this article. A general description is given of the conditions which must be met in the thermal design of such heat exchangers and experimental techniques for obtaining reliable heat-transfer data are mentioned. Finally, details of an experiment designed to justify the use of theoretical analysis of fin efficiency are presented.

THE purpose of the heat exchangers is, of course, to extract heat from the reactor coolant gas (carbon dioxide at a pressure of 10 to 20 atm.) and transfer it to water and steam. This type of heat exchanger is in effect a boiler and is known as a steam-raising unit (s.r.u.). Heat is removed in the s.r.u. from a clean gas whose highest temperature is about 770°F., all the heat transfer being by forced convection to finned tube banks. The assisted circulation or *La Mont* type has found favour, mainly due to its stability and ease of operation.

Generation of steam is at two pressures, and Fig. 1 is a diagrammatic sketch showing the principal components of a dual-pressure steam cycle with reheat at the same pressure as the low-pressure steam generation. This is achieved by expanding h.p. superheated steam in a back-pressure turbine, the power delivered by this turbine being used to drive the gas circulator. This turbine exhausts to the l.p. system in the steam-raising unit. Fig. 2 is a representation of the complete heat-exchanger process in which gas and steam/water temperatures are plotted as ordinates against the heat supplied to the steam/water system, whilst Fig. 3 shows the arrangement of heat-transfer surface within the s.r.u.

Commencing at the feed-water inlets, there are two economisers in parallel in which both h.p. and l.p. feed-water streams are raised to a temperature corresponding to the saturation pressure in the l.p. drum. The l.p. feed is then taken directly into the drum and the h.p. feed to a second-stage economiser above the l.p. evaporator. The h.p. feed water undergoes further heating in this

* *Simon-Carves Ltd.*

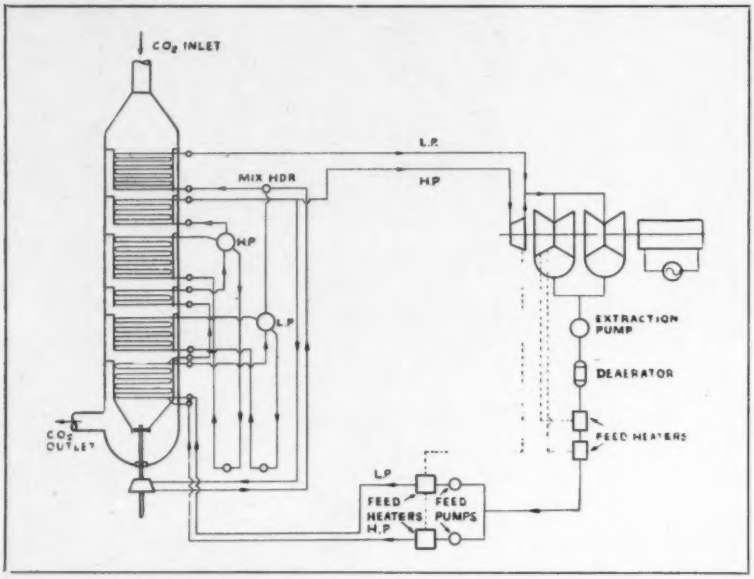


Fig. 1. Arrangement of components in a dual-pressure steam cycle

second economiser until it attains a temperature corresponding to the saturation pressure in the h.p. drum. After evaporation, the h.p. steam is superheated in a bank of tubes immediately above the evaporator. The l.p. saturated steam mixes with the exhaust steam from the gas-circulator turbine and the combined steam is superheated in the final stage above the h.p. superheater. In effect, therefore, there are three essentially different types of heat exchangers to be designed, *viz.* economisers, evaporators and superheaters.

Thermal design

The heat exchangers are of the cross-flow type and utilise finned tubing arranged in either 'staggered' or 'in-line' arrangements. The need for extended surfaces is indicated chiefly by the different order of heat-transfer coefficients on the steam and gas sides. In evaporators and economisers, values of these coefficients on the steam/water side may range from 1,000 to 3,000 B.T.U./sq.ft.hr.°F., whereas on the gas side they will be of the order of 60 to 80 B.T.U./sq.ft.hr.°F. However, in the superheaters the heat-transfer coefficient on the steam side will be less than 200 B.T.U./sq.ft.hr.°F., depending on the steam pressure and, consequently, there is not such a good case for extended surfaces.

For each section of the s.r.u. it is necessary to complete a heat balance and to calculate a mean temperature difference, $\Delta\theta_m$. This calculation is important, since the size of the heat exchanger is influenced directly by it. It will be seen from Fig. 3 that the economisers and superheaters are arranged for counterflow of water/steam and gas. The evaporators are also arranged for counterflow, but they must be considered in two separate sections, since water enters the evaporator below the saturation temperature corresponding to the pressure at that point. This is due to the combined influence of the circulating pump and the gravitational head of water below the steam drum. Thus the water entering the evaporator must first be heated until its temperature rises to a point at which boiling can commence. This point makes a convenient division of the evaporator into a pre-heating section and an evaporating section.

Mean temperature differences in the economisers and the evaporator sections are calculated, without serious error, as the logarithmic mean of the terminal temperature differences.

$$\Delta\theta_m = \frac{\Delta\theta_1 - \Delta\theta_2}{ln(\Delta\theta_1/\Delta\theta_2)} \quad \ldots\ldots\ldots (1)$$

$$\text{or } \Delta\theta_m = \frac{q}{\int dq/\Delta\theta} \quad \ldots\ldots\ldots (2)$$

For greater accuracy a correction factor may be applied to allow for the effects of cross-flow,[1] but the error in ignoring this is likely to be less than 1% in the economisers and nil in the evaporators. In the superheaters, however, a significant error arises from the use of equation (1) which is based on the assumption that the specific heat of each fluid is constant. Owing to variations in the specific heat of steam the true mean temperature difference in the h.p. superheater may exceed that calculated from equation (1) by as much as 7%. Thus in superheaters the only satisfactory method of determining $\Delta\theta_m$ is step-by-step integration of equation (2).

The quantity of surface required to construct each section of the s.r.u. is calculated from the equation:

$$q = USL\Delta\theta_m \quad \ldots\ldots\ldots (3)$$

Thus the product US is the heat-transfer rate/ft. of tube/°F. temperature difference between the two fluids,

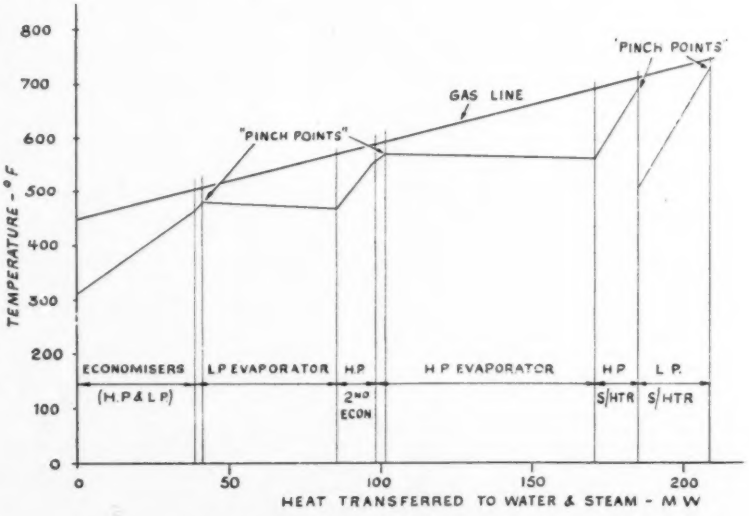


Fig. 2. Temperature diagram for a typical s.r.u.

NOMENCLATURE

A	= A function of Prandtl number	Dimensionless
a	= A constant	"
b	= Half the fin thickness	Ft.
C_p	= Specific heat of gas at constant pressure	B.T.U./lb.°F.
D	= Fin height	Ft.
d	= Tube diameter	"
f	= Pressure drop coefficient	Dimensionless
G	= Mass flow of gas based on the face area of the tube bank	Lb./sq.ft.hr.
g	= Acceleration due to gravity	Sq.ft./sec.
h	= Heat-transfer coefficient	B.T.U./sq.ft.hr. °F.
k_g	= Thermal conductivity of gas	B.T.U./sq.ft.hr. °F./ft.
k_m	= Thermal conductivity of metal	" " "
L	= Length of tube	Ft.
l	= Position in tube bank	"
M	= An experimentally derived factor	Dimensionless
n	= Number of rows of tubes in the direction of flow	
p	= Static pressure	Lb./sq.ft. abs.
Pr	= Prandtl number $= C_p\mu/k_g$	Dimensionless
q	= Heat transfer rate	B.T.U./hr.
R	= Duct radius	Ft.
r	= Radial positions	"
Re	= Reynolds number $= Gd/\mu$	Dimensionless
S	= Surface area per foot of tube	Ft.
S_T	= Transverse tube pitch	"
St	= Stanton number $= h/Gc_p$	Dimensionless
U	= Overall heat-transfer coefficient	B.T.U./sq.ft.hr °F.
V	= Maximum velocity	Ft./hr.
v	= Local velocity	"
w	= Tube wall thickness	Ft.
X	= Area of heat-exchanger surface	Sq.ft.
$\alpha\ \alpha_1$	= Constants	Dimensionless
$\Delta\theta$	= Temperature difference	Deg. F.
$\Delta\theta_f$	= Temperature drop over condensate film	"
$\Delta\theta_m$	= Mean temperature difference between the finned surface and the fluid	"
Δ_p	= Pressure drop over n rows	Lb./sq.ft.
θ_g	= Bulk gas temperature	Deg. F.
θ_s	= Mean outside tube wall temperature	"
μ	= Absolute viscosity	Lb./ft.hr.
ρ	= Fluid density	Lb./cu.ft.
φ	= Weighted fin efficiency	Dimensionless

Subscripts (unless otherwise indicated):

1	= Upper value
2	= Lower value
i	= Inside
m	= Mean

and is a convenient parameter for comparing the performance of two tubes at similar values of fluid flow rates.

Overall heat-transfer coefficient

Clearly, then, the calculation of the quantity US is of tremendous importance to the designer, influencing as it does the size of the heat exchanger. The overall heat-transfer coefficient U is related to the individual heat-transfer coefficients by the equation:

$$\frac{1}{US} = \frac{1}{h\varphi S} + \frac{1}{h_i S_i} + \frac{w}{k_m S_m} \quad (4)$$

The internal heat-transfer coefficient h_i in the economisers and superheaters may be found from well-established equations[2] such as:

$$St.Pr^{\frac{2}{3}} = 0.023\ Re^{-0.2} \quad \ldots\ldots (5)$$

or the more accurate and theoretically founded equation quoted by Eckert:[3]

$$St = \frac{0.0396\ Re^{-0.25}}{1 + ARe^{-0.125}(Pr - 1)} \quad \ldots (6)$$

where A is a function of Pr. In the evaporators, the internal heat-transfer coefficient is difficult to determine accurately, since there are many factors involved and experimental results are not in close agreement. However, the following dimensional equation of Bogdanov is given by Collier[4] and may be used satisfactorily for this purpose when $q/S_i \leq 36{,}870$ B.T.U./sq.ft.hr.:

$$h_i = 0.0669\ (q/S_i)^{0.7} p^{0.3} \quad \ldots\ldots (7)$$

It is the determination of the value of the external heat-transfer coefficient h which presents so much difficulty in design, depending as it does on so many aspects of the tube and fin geometry in addition to the pitch of the tubes. Satisfactory values for h can only be obtained by experiments conducted under laboratory conditions with close co-operation between research and design staff. Fin efficiency φ is a function of fin and tube geometry, thermal conductivity of fin material, and also h. It may be calculated using the mathematical curves of Gardner[5] or it may be derived experimentally.

Factors for fouling both of the inner tube wall and the external fins may be included in equation (4) at the designer's discretion. These must be very small for heat exchangers of the type under discussion, operating as they do with gas and water of the highest purity and with conditions so carefully controlled. Consequently it is usual to ignore these fouling factors and include allowance for this and other unknowns by installing a small fraction of additional surface.

Of similar importance in s.r.u. design, as determining the heat-transfer performance, is the determination of the gas-side pressure drop, which may be expressed for a bank of finned tubes as:

$$\Delta p = fnG^2/2g\rho \quad \ldots\ldots\ldots\ldots (8)$$

where f is the pressure-drop coefficient

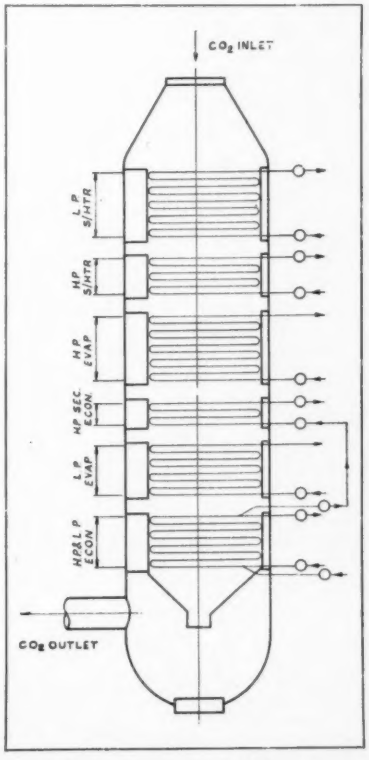


Fig. 3. Section of a typical s.r.u.

determined experimentally. The gas density is evaluated at the bulk gas temperature and may be taken as a length mean:

$$\rho_m = \frac{1}{l}\int_0^l \rho dl$$

Gas-side heat-transfer coefficient

The basic experimental method and apparatus have been described elsewhere.[6] Some improvements have since been made in what has now become the routine measurement of the gas-side heat-transfer coefficient for a bank of finned tubes. The tests are carried out on banks of tubes in a nominally 20-in.-square open-circuit wind tunnel. The banks are made up by locating the tubes vertically between wooden boards which form the top and bottom of the tunnel working section. One of the wind-tunnel walls is movable so that the tunnel width may be adjusted to suit the transverse pitch of the tubes under test. In the case of staggered tube banks, the bank is completed by half-section tubes fitted at the tunnel walls. The mass flow of air in the tunnel is calculated from pitot measurements upstream of the tunnel working section.

The heat-transfer characteristics are normally determined for a finned tube placed centrally in the seventh row of an eight-row-deep bank. Atmospheric air is drawn over the tubes, whilst the tube under test is heated with slightly superheated steam at just above atmospheric pressure. The amount of condensate is a measure of the heat transferred.

In calculating the heat-transfer rate, allowances are made for superheat of the steam, under-cooling of the condensate, and radiation and end losses. The outside tube surface temperature, θ_s, is calculated by deducting from the saturated steam temperature allowance for the temperature drops over the condensate film and tube wall. The temperature drop over the condensate film was determined experimentally for a 20-in.-long tube; the data were represented by:

$$\Delta\theta_f = (q/2{,}200\ S_i L)^{\frac{1}{4}} \quad \ldots\ldots\ (9)$$

which agrees very closely with the McAdams equation:[7]

$$\Delta\theta_f = (q/4{,}000\ S_i L^{\frac{1}{2}})^{\frac{2}{3}} \quad \ldots\ldots\ (10)$$

During condensation some magnetite is deposited on the inner wall of the tube, but its effect on $\Delta\theta_f$ is almost negligible if before each day's tests the bore is cleaned with dilute hydrochloric acid, scrubbed, and flushed with water. This also ensures film-

This article will be concluded in the March issue of CHEMICAL & PROCESS ENGINEERING

wise condensation of the steam. The temperature drop over the tube wall is calculated assuming a uniform heat flux. The average air temperature θ_g is the arithmetic mean of the air temperatures before and behind the tube.

The heat-transfer rate between a gas and unit length of a finned tube may be expressed as:

$$q = \int_0^s h\Delta\theta dS$$

where $\Delta\theta$ is the local temperature difference between the gas and finned surface. For a uniform h:

$$q = h\int_0^s \Delta\theta dS$$
$$= h\Delta\theta_m S$$
$$= h\varphi(\theta_s - \theta_g)S$$

where $\Delta\theta_m$ is the mean difference between the average gas temperature and the finned surface temperature. The heat-transfer rate q is determined experimentally for different mass flows of air, whilst θ_s and θ_g are estimated as indicated above, so $h\varphi S$ is derived as a conductance term. The area of the surface S may be calculated, but h and φ are inseparable by any simple means. If it is required to refer the mean heat-transfer coefficient h to some fluid property, other than that at which the test has been carried out, by a non-dimensional Nusselt equation:

$$\frac{hd}{k_g} = \alpha_1\left(\frac{Gd}{\mu}\right)^a\left(\frac{C_p\,\mu}{k}\right)^{\frac{1}{3}} \quad \ldots\ (11)$$

it is necessary to evaluate the weighted fin efficiency φ, which is equal to $\Delta\theta_m/(\theta_s - \theta_g)$. Gardner[5] shows that, by making various assumptions, the most significant one being that of assuming a uniform heat-transfer coefficient, the weighted fin efficiency may be calculated for various fin shapes. From a curve of h against $h\varphi$, a value of h is obtained for a particular value of $h\varphi$. This value of h may be used in the above Nusselt equation (11), where α_1 and a are constants, G is the mass flow based on the face area of the bank, and air-film properties are evaluated at the mean film temperature, $\theta_g + \frac{1}{2}(\theta_s - \theta_g)\varphi$.

There is a row-to-row variation in heat-transfer coefficient which is measured by condensing steam in the centre tube of each row of the bank in turn. For a staggered bank of annular or spirally wound finned tubes, the mean coefficient increases to a constant value by about the fourth row and remains constant up to the last row of the bank, where it is again lower. This variation may be allowed for by using a factor to express the mean coefficient for n rows as a ratio to that at the last row but one.

The heat-transfer rate between *this* finned-tube bank and a gas other than air, for example carbon dioxide, whose properties are denoted by a dash, is obtained at the same Reynolds number using:

$$h' = h(k_g'/k_g)(Pr'/Pr)^{\frac{1}{3}}$$

For this value of h' there is a unique value of φ', and therefore of $h'\varphi'$, the conductance in carbon dioxide.

It is estimated that the experimental error, arising mainly from errors in the estimation of temperature drops over the condensate film and tube wall, is about $\pm 2\%$. In transposing experimental data to design conditions using pressurised carbon dioxide, the principal errors arise from the evaluation of fin efficiency and the thermal conductivity of air and of carbon dioxide. The probable error on design data is reckoned to be $\pm 6\%$.

Acknowledgments

The authors would like to thank the General Electric Co. Ltd. and Simon-Carves Ltd. for permission to publish this paper, and the author's present and past colleagues at Erith, in particular Mr. A. Lymer, for their contribution.

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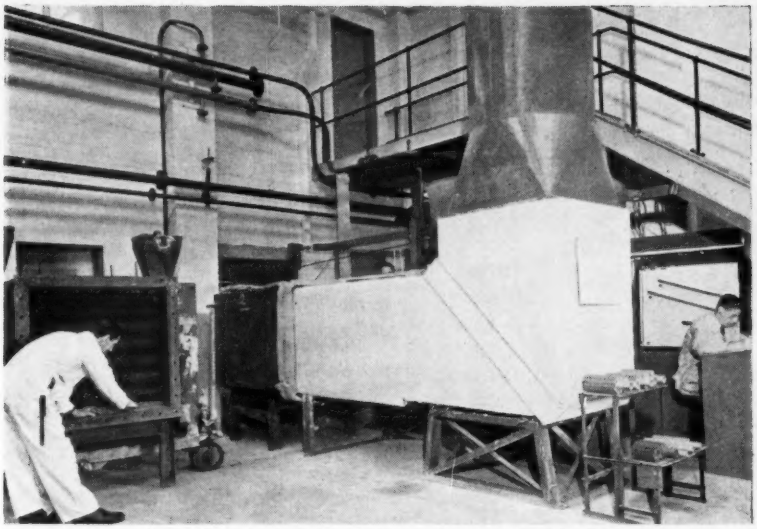
Transient Behaviour of Counterflow Heat Exchangers

Part 1



Atmospheric pressure test rig for transient heat investigations

CPE feature — Heat exchangers

By F. L. Carvalho,* D.F.H.(Hons.), Grad.I.E.E.

In recent years a great deal of interest has centred on the transient performance of heat exchangers. In the first part of this article the author discusses the whole problem from an engineering standpoint and discusses in some detail the possible methods of solving the temperature-time history of the two fluids and the assumptions that most affect the accuracy of the final solution.

THIS article deals only with counterflow heat exchangers, where the heat is transferred from one fluid to another due to a temperature difference which exists between them. It will be assumed that there is no change of phase and that all the heat transferred is due to forced convection only, with no radiation effects present. It is possible to deal with the problem of unsteady-state radiant heat transfer between two fluids, by representing the radiation mechanism by an equivalent linear system,[1] but this will not be illustrated in the present article.

Description of physical events

For the purpose of illustration we will consider an air-to-water heat exchanger, the air being the primary or hot fluid, passing over a straight metal tube which contains the secondary fluid, water. Assume the tube to be horizontal with the cold water entering at the left-hand end and the hot air passing over the tube axially from right to left. This is the simplest model of a pure counterflow heat exchanger, the distance between the ends of the tube being known as the zone of heat transfer. As the air passes over the tube it will transfer heat to the metal due to the difference in temperature, and likewise the metal will lose heat to the water. In the steady operating condition the heat entering the metal is equal to the heat leaving it. These processes are distinct and independent and in the design of heat-transfer equipment are assessed separately from experimentally obtained published data.[4, 5]

In order to establish the temperatures of the air, metal and water at any given distance from one end of the tube, it is necessary to examine an infinitesimal length of the tube, *i.e.* a very small heat exchanger of, say, length dx.

Heat lost by air $= mc_g d\mu$ B.T.U./hr.

Heat gained by metal $= \dfrac{R_g S_g}{L_w}\, dx\, (\mu - \varphi)$ B.T.U./hr.

and, in the steady state,

$$mc_g d\mu = \frac{R_g S_g}{L_w}\, dx\, (\mu - \varphi) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Similarly, a heat balance between the tube and the water yields

$$\frac{R_w S_w}{L_w}\, dx\, (\varphi - \theta) = Mc_w\, d\theta \quad \ldots\ldots\ldots\ldots\ldots (2)$$

Also we have

$$\frac{R_g S_g}{L_w}\, dx\, (\mu - \varphi) = \frac{R_w S_w}{L_w}\, dx\, (\varphi - \theta) \quad \ldots\ldots (3)$$

Solution of the differential equation system (equations (1) and (2)) yields an exponential type temperature distribution for each fluid as a function of distance x from one end of the tube. Knowing μ and θ, φ is obtained from equation

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(3). A typical temperature diagram is shown in Fig. 1. The major assumption in the above model is that the specific heat of each fluid does not vary in the zone of heat transfer; another assumption of lesser importance is that the coefficients of heat transfer are also constant over the path considered.

It is important to know the steady-state temperatures in the heat exchanger before one is able to evaluate the transient performance under given conditions. Furthermore, the accuracy of the assumptions made in the transient analysis is more readily assessed by knowing the range of temperatures dealt with. The temperature diagram of Fig. 1 is known as the exact temperature distribution, as distinct from the ' approximate ' temperature distribution which is discussed in the following paragraphs. The term ' exact ' used in the text here refers to the solution of a ' differential ' equation such as equation (1), and does not imply coincidence of calculated temperatures and test data on a model heat exchanger.

Approximate temperature distribution

The reasons for discussing the approximate temperature distribution will not be apparent at this stage, but, as will be found later, is the starting point in the method of calculating transients in heat exchangers.

To calculate the approximate temperature distribution we suppose the original straight metal tube to be replaced by a large number of ' small ' heat exchangers of the same types, in series. Mathematically we have replaced the infinitesimal distance dx of our original model by a finite distance Δx ft. Writing the heat balance equations for one section of this series of small heat exchangers of length Δx, we get:

Heat lost by primary fluid $= mc_g(\mu_{x+\Delta x} - \mu_x)$ B.T.U./hr.

Heat transferred to metal =

$$\frac{R_g S_g}{L_w} \Delta x(\mu_{x+\frac{1}{2}\Delta x} - \varphi_{x+\frac{1}{2}\Delta x}) \text{ B.T.U./hr.}$$

and, in the steady state,

$$mc_g(\mu_{x+\Delta x} - \mu_x)$$
$$= \frac{R_g S_g}{L_w} \Delta x(\mu_{x+\frac{1}{2}\Delta x} - \varphi_{x+\frac{1}{2}\Delta x}) \text{ B.T.U./hr.} \quad \ldots\ldots (1a)$$

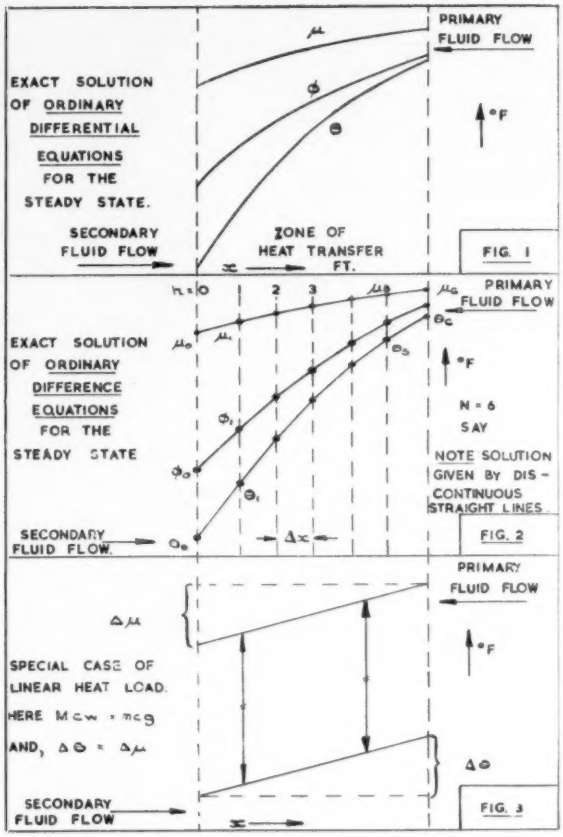
and, as before, we obtain for the metal-to-water heat transfer, in the steady state,

$$\frac{R_w S_w}{L_w} \Delta x(\varphi_{x+\frac{1}{2}\Delta x} - \theta_{x+\frac{1}{2}\Delta x})$$
$$= Mc_w(\theta_{x+\Delta x} - \theta_x) \text{ B.T.U./hr.} \quad \ldots\ldots (2a)$$

and

$$\frac{R_g S_g}{L_w} \Delta x(\mu - \varphi)_{x+\frac{1}{2}\Delta x}$$
$$= \frac{R_w S_w}{L_w} \Delta x(\varphi - \theta)_{x+\frac{1}{2}\Delta x} \text{ B.T.U./hr.} \quad \ldots\ldots (3a)$$

Equations (1a), (2a) and (3a) are known as ' difference ' equations since they are based on linear differences. These equations have solutions in closed form. If the heat-exchanger model chosen is analysed for steady-state temperatures by application of equations (1a), (2a) and (3a) we obtain the ' approximate ' temperature distribution. For the case of six equal sections, the temperature diagram would look like that shown in Fig. 2. The important point to note is that the lines joining the temperatures are all straight in this case.


EXACT SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS FOR THE STEADY STATE.
PRIMARY FLUID FLOW
SECONDARY FLUID FLOW
ZONE OF HEAT TRANSFER FT.
FIG. 1
EXACT SOLUTION OF ORDINARY DIFFERENCE EQUATIONS FOR THE STEADY STATE
N = 6 SAY
NOTE SOLUTION GIVEN BY DISCONTINUOUS STRAIGHT LINES
FIG. 2
SPECIAL CASE OF LINEAR HEAT LOAD.
HERE Mcw = mcg
AND, Δθ = Δμ
FIG. 3

Comparison of temperature diagrams

Heat-exchanger design engineers are familiar with the logarithmic mean temperature difference (LMTD) technique for evaluating overall heat transfer and assigning surfaces to meet a required heat duty. The LMTD formula is in fact derived from the solution to equations (1) to (3). They are perhaps not so familiar with the arithmetic mean temperature difference (AMTD). In the transient calculations to follow, it is the AMTD technique which is used; the reasons for this will be given later.

It is important to note that the approximate temperature diagram does not coincide with the exact temperature diagram. This may be seen quite easily by superposing Fig. 1 on Fig. 2. Consider Section 1. The straight line from θ_1 to θ_o represents the tangent to the exponential θ curve at $x = 0$. Hence θ_1 in Fig. 2, will be greater than the corresponding θ in Fig. 1. This is true for θ_2, θ_3, etc., but as one proceeds further along the tube the situation gets worse, since the error in the previous section gets ' added ' in. The net result is an error in heat balance. This does not imply that the heat lost by the air is not equal to the heat gained by the water. This in fact must be so by equations (1a) to (3a). It means that the overall heat transfer is different depending on whether one uses the exact temperature distribution (using LMTD technique) or the approximate temperature distribution, *i.e.* using AMTD technique.

Exact heat transfer, $Q_E = R_o S_g$(LTMD) B.T.U./hr.

Approximate heat transfer, $Q_A = R'_o S_g$(AMTD) B.T.U./hr.

$$Q_E < Q_A \quad \text{and} \quad R'_o \neq R_o$$

where R_o = overall coefficient of heat transferred to the air-side surface area S_g, B.T.U./sq.ft.hr.°F.; R'_o defined as the apparent overall coefficient of heat transfer referred to S_g, B.T.U./sq.ft.hr.°F. (R'_o does not appear in the calculations at all, but may be evaluated from the temperature diagram of the type shown in Fig. 2.)

Approximate steady state temperature distribution

To obtain a formula for working out the steady temperature distribution of the two fluid streams and the metal it is necessary to obtain a solution to a set of equations of the type (1*a*) to (3*a*). The actual derivation of the solutions is long and tedious, and hence only the results are quoted which will enable the temperatures to be worked out at any number of chosen points.

Secondary fluid temperature distribution ($t = 0$)

$$\theta_h = \frac{1}{1 - \alpha\beta^N}\left[(1 - \beta^h)\,\mu_N + (\beta^h - \alpha\beta^N)\theta_o\right] \text{°F.} \quad \ldots\ldots (1b)$$

Primary fluid temperature distribution ($t = 0$)

$$\mu_h = \frac{1}{1 - \alpha\beta^N}\left[(1 - \alpha\beta^h)\,\mu_N + \alpha\,(\beta^h - \beta^N)\theta_o\right] \text{°F.} \quad \ldots (2b)$$

Wall temperature distribution ($t = 0$)

$$\varphi_h = c_o\mu_h + d_o\theta_h \text{ °F.} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3b)$$

where

$c_o = \dfrac{R_gS_g}{R_gS_g + R_wS_w}$

$d_o = 1 - c_o$

h = unit periodic function = 0, 1, 2 ..... N

$\beta = \dfrac{R_oS_g}{Mc_wN}\left(\dfrac{Mc_w}{mc_g} - 1\right) + 1$

$\alpha = Mc_w/mc_g$

N = Number of equal divisions of heat exchanger in direction of fluid flow path

θ_o = Secondary fluid inlet temperature ($t = 0$)

μ_N = Primary fluid inlet temperature ($t = 0$)

R_o = Overall coefficient of heat transfer referred to the primary side surface area, S_g

The criteria for a satisfactory solution are: (i) β must be positive and (ii) $mc_g \neq Mc_w$. If $mc_g = Mc_w$ we obtain the special case of linear heat load, when the solution to the difference equation system (1*a*) to (3*a*) is not satisfied by the formulae given above (see Fig. 3).

This implies that, for a given heat load, the number of sections N must be such that the value of β is greater than zero. In practical terms the implication is that the more exponential the temperature distribution the greater should be the value of N.

Heat balance in the unsteady state

We have seen that, in the case of a heat exchanger operating in the steady state, the heat which passes from the hot fluid to the metal tube is exactly equal to the heat which passes out of the tube into the water.

If conditions in the system are such that there is an inequality in this transference of heat, there will be a build-up or decay of heat in those parts of the exchanger which are not able to follow the new conditions immediately. The tube bank which has finite heat capacity will therefore store energy and the rate at which its temperature increases or decreases will depend on the heat capacity of the metal.

Consider again the original small heat exchanger of axial length dx ft.

The basic rate equation for the tube bank may be written:

Heat entering metal from gas side minus heat loss to water = rate of change of heat in metal.

$$\frac{R_gS_g}{L_w}\,dx(\mu - \varphi) - \frac{R_wS_w}{L_w}\,dx\,(\varphi - \theta) = \frac{C_T}{L_w}\frac{\partial\varphi}{\partial t}dx \text{ B.T.U./hr.}$$

where C_T = thermal capacity of the tube bank, B.T.U./°F.

The water temperature equation is derived below:

Let θ = temperature of water at the centre of the element.

Heat entering element of water of length dx ft. from water stream, °F.

$$Mc_w\left(\theta - \tfrac{1}{2}\frac{\partial\theta}{\partial x}dx\right) \text{ B.T.U./hr.}$$

Heat leaving small exchanger

$$Mc_w\left(\theta + \tfrac{1}{2}\frac{\partial\theta}{\partial x}dx\right) \text{ B.T.U./hr.}$$

Heat entering from metal

$$\frac{R_wS_w}{L_w}\,dx\,(\varphi - \theta) \text{ B.T.U./hr.}$$

The sum total of these heat flows is equal to the rate of change of energy in the water within the element dx

$$= \frac{C_w}{L_w}\frac{\partial\theta}{\partial t}\,dx$$

Rearranging the above equations, we get:

$$\frac{\partial\theta}{\partial t} + V_w\frac{\partial\theta}{\partial x} = \frac{R_wS_w}{C_w}\,(\varphi - \theta) \text{ °F./hr.}$$

The gas temperature equation is obtained more simply

NOMENCLATURE

The following symbols appear in the text. Those symbols which do not arise in the general theory are omitted in this list, but are explained as they arise.

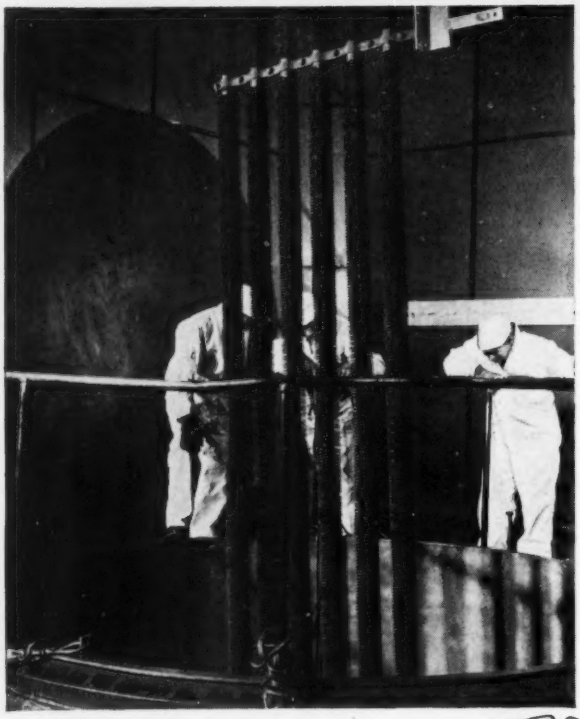
Parameter	*Secondary fluid*	*Primary fluid*	*Tube bank*	*Units*
Mass flow ..	M	m		lb./hr.
Velocity	V_w	v_g		ft./hr.
Specific heat at constant pressure	c_w	c_g		B.T.U./lb. °F.
Film coefficient of heat transfer	R_w	R_g		B.T.U./sq.ft./hr.°F.
Total surface available to heat transfer ..	S_w	S_g		sq.ft.
Temperature ..	θ	μ	φ	°F.
Total thermal capacity ..	C_w		C_T	B.T.U./ft.
Flow path length	L_w			ft.

Other symbols are:

η = Fin efficiency, dimensionless
h = Unit periodic function, or counter in space
x = Space as measured from LHS in Fig. 1; ft.
Δx = Finate increment in space
$\Delta\tau$ = „ „ „ time
$N = \dfrac{L_w}{\Delta x}$, number of equal sections into which heat exchanger is divided.
t = time, hr.

Heat-exchange is our business

Production of Babcock helically-finned heat-exchanger tubing by semi-automatic resistance welding.



The principle of heat-exchange is fundamental to a multitude of industrial processes, from simple heating or cooling to high-pressure, high-temperature steam-raising for power generation, or the complex cycles of oil-refining and chemical processing.

Production costs, with whatever process, are closely related to efficient application of the principle, through plant designed from specialized knowledge and long practical experience.

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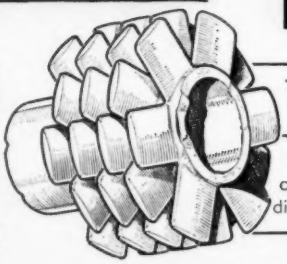
Manufactured in 1½ in., 2 in. or greater outside diameter, with fin-heights from ½ in. to 1 in. and fin-thicknesses from 1/16 in. to 3/32 in. Pitch, up to 6 fins per inch. Typical examples are given here. Test performance figures available if required.



TUBE SIZE	FIN DIMENSIONS	FIN PITCH	SURFACE AREA PER FOOT
2 in. outside diameter	5/8 in. high, 5/64 in. thick	4 per inch	3·6 sq. ft.
	5/8 in. high, 5/64 in. thick	6 per inch	5·14 sq. ft.

BABCOCK & WILCOX LTD., BABCOCK HOUSE, 209 EUSTON ROAD, LONDON, N.W.1.

if we assume that, by virtue of its extremely small thermal capacity, it is able to change its temperature instantaneously. The gas equation for heat loss will be:

$$mc_g\left(\mu + \tfrac{1}{2}\frac{\partial\mu}{\partial x}dx\right) - mc_g\left(\mu - \tfrac{1}{2}\frac{\partial\mu}{\partial x}dx\right) = \frac{R_gS_g}{L_w} \cdot dx \cdot (\mu - \varphi) \quad \text{B.T.U./hr.}$$

Since the assumption of zero heat leakage is made, there are only three equations to be solved.[2]

By rearranging the unsteady-state heat balance equations, the following system of partial differential equations results:

$$\frac{\partial\theta}{\partial t} + V_w\frac{\partial\theta}{\partial x} = \frac{R_wS_w}{C_w}(\varphi - \theta) \quad \ldots\ldots\ldots\ldots (1c)$$

$$\frac{\partial\varphi}{\partial t} = \frac{R_gS_g}{C_T}(\mu - \varphi) - \frac{R_wS_w}{C_T}(\varphi - \theta) \quad \ldots\ldots (2c)$$

$$\frac{\partial\mu}{\partial x} = \frac{R_gS_g}{mc_gL_w}(\mu - \varphi) \quad \ldots\ldots\ldots\ldots\ldots\ldots (3c)$$

There is no general solution to equations (1*c*) to (3*c*) in closed form known to the author.

It should here be stated that, if a solution were obtainable, the initial conditions (*i.e.* the temperatures at time, $t = 0$) would be given by the solution of equations (1) to (3), *i.e.* exponential curves of the type shown in Fig. 1.

Since an exact solution is ruled out, the next step is to obtain an approximate solution. The partial differential equations may be approximated in a number of ways and the results obtained will be different according to the actual approximations which are used. The simplest and most commonly used engineering approximation to first order derivatives is as follows (others, however, are possible[3]):

$$\frac{\partial\theta}{\partial x} \simeq \frac{\theta_{x+\Delta x} - \theta_x}{\Delta x} \quad \text{°F./ft.}$$

for the space derivative, and

$$\frac{\partial\theta}{\partial t} \simeq \frac{\theta_{t+\Delta T} - \theta_t}{\Delta T} \quad \text{°F./hr.}$$

for the time derivative. Writing this type of approximation for each variable and rearranging terms, we obtain the following system of partial finite difference equations:

$\theta_{x+\Delta x}$ has been abbreviated to θ_{h+1}, etc.

θ_o is the incoming water temperature, which is a known boundary condition

μ_N is the incoming gas temperature, *i.e.* the temperature at the end of the *n*th section. For a counterflow heat exchanger this is a boundary condition, or known temperature.

$$\theta_{h+1}^{t+\Delta T} = \Delta T\frac{R_wS_w}{C_w}\varphi_h^t + \Delta T\left(\frac{V_w}{\Delta x} - \frac{R_wS_w}{C_w}\right)\theta_h^t + \left(1 - \frac{\Delta T}{\Delta x}V_w\right)\theta_{h+1}^t \text{ °F} \quad \ldots\ldots\ldots\ldots (1d)$$

$$\varphi_h^{t+\Delta T} = \left(1 - \Delta T\frac{R_wS_w + R_gS_g}{C_T}\right)\varphi_h^t + \Delta T\frac{R_gS_g}{C_T}\mu_h^t + \Delta T\frac{R_wS_w}{C_T}\theta_h^t \text{ °F.} \quad \ldots\ldots\ldots\ldots (2d)$$

$$\mu_h^t = \left[\frac{1}{1+(R_gS_g/mc_gN)}\right]\mu_h^t + \left[\frac{R_gS_g/mc_gN}{1+(R_gS_g/mc_gN)}\right]\varphi_h^t \text{ °F.} \quad \ldots\ldots\ldots\ldots (3d)$$

$$h = 0, 1, 2, \ldots\ldots\ldots (N-1)$$

Equations (1*d*) to (3*d*) represent the equivalent finite difference system to the exact system (1*c*) to (3*c*). This approximate system of equations is in fact a set of algebraic equations which may be solved iteratively, provided the boundary conditions, *i.e.* the incoming fluid temperatures, are known. The variables to be solved are the temperatures θ, φ and μ at all points in the heat exchanger, for a given set of data.

Before discussing the physical aspects of these equations, it will be noted that a better mathematical model than that represented by equations (1*d*) to (3*d*) can be obtained as follows. Consider the direction of fluid flow. The water passes along the tube from left to right. Equation (1*d*) when iterated solves the water temperature $\theta_1^{t+\Delta T}$, assuming that the terms on the right-hand side of equation (1*d*) are known. The second iteration will give θ_2, *i.e.* by putting $h = 1$, and so on. The temperatures θ_1, θ_2, etc., are solved in turn until the fluid passes out of the tube. The water temperature is computed in such a fashion as to follow the water flow direction. On the other hand, the numerical order of gas temperature calculation as indicated by equation (3*d*) is contrary to the direction of flow. On the gas side it would be better to iterate from right to left. If equation (3*d*) is modified with regard to direction of iteration, a closer approximation to the physical system results, without incurring any mathematical inconsistency. Modifying equation (3*d*) to obtain the correct direction of iteration we obtain:

$$\mu_{k+(N-1)}^t = \frac{R_gS_g/mc_gN}{1+(R_gS_g/mc_gN)}\varphi_{k+(N-1)}^t + \frac{1}{1+(R_gS_g/mc_gN)}\mu_{k+N}^t \quad \ldots\ldots\ldots (3d\dagger)$$

where $k = -h$ and $h = 0, 1, 2, \ldots\ldots\ldots\ldots (N-1)$.

Equations (1*d*), (2*d*) and (3*d*†) give a more representative picture of the counterflow heat exchanger, since the effect of changing boundary temperatures θ_o and μ_N will now be immediately felt in the model just as they are in the physical system.

Before commencing the iteration, it is necessary to establish the initial temperature distribution of gas, metal and water. The initial values are obtained by applying the formulae (1*b*) to (3*b*) to the exchanger in the steady state before the disturbance is applied. These formulae will yield the approximate temperature distribution at time $t = 0$, and these values of temperature are required to enable values at time $t + \Delta T$ to be evaluated using the equations (1*d*) to (3*d*†).

Having obtained the gas, metal and water temperatures throughout the heat exchanger at each mesh point in Fig. 2, for time $t + \Delta T$ by use of equations (1*d*) to (3*d*†), the resulting distribution represents the temperatures at time $t + \Delta T$. These values are then fed into the equations again and, after another complete cycle of iteration, the temperatures are obtained at time $t + 2\Delta T$, and so on. The iteration continues in such cycles until it appears that the temperature distribution remains more or less as it was for the previous iteration. This indicates that the new steady state has been established. The foregoing remarks

have presupposed that there has been only a step change in either a fluid inlet temperature or mass flow, or both occurring simultaneously. The method becomes more apparent in the worked example. However, before proceeding to the numerical iteration, it will serve a useful purpose if some physical aspects are examined in relation to the mathematical representation of equations (1*d*) to (3*d*†).

Physical significance of the transient equations

Consider equation (1*d*). This equation evaluates the water temperature throughout the exchanger (at the mesh points) at time $t + \Delta T$ assuming that the temperature at the points we are concerned with in the system are known at time t. The equation is:

$$\theta_{h+1}^{t+\Delta T} = \Delta T \frac{R_w S_w}{C_w} \varphi_h^t$$

$$+ \Delta T \left(\frac{V_w}{\Delta x} - \frac{R_w S_w}{C_w} \right) \theta_h^t + \left(1 - \frac{\Delta T}{\Delta x} V_w \right) \theta_{h+1}^t$$

Before considering the coefficients of each temperature term the following definitions are useful:

$$\frac{C_w}{R_w S_w} = \frac{\text{Water thermal capacity}}{\text{Heat flux factor}} =$$

waterside time constant (assuming constant wall temp.)

$$\frac{\Delta x}{V_w} = \frac{\text{Length of finite exchanger}}{\text{Water velocity}}$$

= water transit time for small element

Stability of the equations (1d) to (3d†)

For the success of the calculations the coefficient of each temperature term must lie between the values zero and +1. This is most important otherwise complex oscillations in temperature distribution will result.[6, 7] The proofs of the stability criteria are not included in this article, but if the following simple rules are followed, a successful iteration is assured:

(1) $0 \leqq$ Coefficient of each temperature term $\leqq 1$

(2) Check numerically that the sum of the coefficients of the temperature terms on the right-hand side of each equation—(1*d*) to (3*d*†)—exactly equals +1.

In order to satisfy Rule (1), ΔT and Δx must be appropriately chosen.

Choice of ΔT and Δx

In order to satisfy Rule (1):

$$\Delta T \leqq \frac{C_w \times 3{,}600}{R_w S_w} \text{ sec.}^* \quad \ldots\ldots\ldots \quad \textit{Criterion 1}$$

The computing time interval ΔT must be less than or equal to the waterside time constant:

$$\frac{V_w}{\Delta x} \geqq \frac{R_w S_w}{C_w \times 3{,}600}$$

$$\text{or} \begin{pmatrix} \text{Water transit} \\ \text{time for one} \\ \text{section} \end{pmatrix} \leqq \begin{pmatrix} \text{Waterside} \\ \text{time,} \\ \text{constant} \end{pmatrix} \quad \ldots\ldots \textit{Criterion 2}$$

$$\text{and} \qquad \frac{\Delta T}{\Delta x} V_w \leqq 1 \qquad \textit{i.e.} \ \frac{\Delta x}{\Delta T} \geqq V_w$$

or computing velocity $\geqq$ water velocity .... *Criterion* 3

The last criterion merely states that the 'speed' of computation must be fast enough to 'catch' the block of water and monitor its temperature before it passes out of one section. Also:

$$\Delta T \leqq \frac{C_T \times 3{,}600}{R_g S_g + R_w S_w} \quad \ldots\ldots\ldots\ldots \textit{Criterion 4}$$

The use of these criteria will become more apparent in the second part of this article where the numerial example is studied. Great care must be exercised to prevent inconsistency of units when converting symbols to numerics.

The conclusion of this article will appear in the March issue of CHEMICAL & PROCESS ENGINEERING

Assumptions

(1) There is no change of phase, $0 < t < \infty$.

(2) The exchanger is represented by a pure counterflow model.

(3) Metal conductance across the wall is infinite.

(4) The tube may be considered as a thin annulus with finite heat capacity, this capacity being an indirect function of fin efficiency when extended surfaces are employed.

(5) The fin efficiency does not alter during the transient.

(6) The specific heats of both fluids are independent of temperature and pressure in the range examined.

(7) Heat-transfer coefficients are not functions of position [*i.e.* R_w and $R_g \neq f(x)$]; $0 < t < \infty$.

(8) Heat-transfer coefficients are independent of temperature during the transient.

(9) Heat is lost by the gas only to the tube wall and water, *i.e.* no external losses of heat.

(10) There is no axial heat flow in the metal.

(11) Temperature gradients in the two fluid streams perpendicular to the fluid flow paths exist only in the boundary layer, *i.e.* there is no temporary or permanent stratification; mixing is complete.

Acknowledgments

The author wishes to thank the management of Babcock & Wilcox Ltd. for permission to publish this article.

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Materials of Construction for Chemical Plant

In the article on Platinum in the series 'Materials of Construction for Chemical Plant', which appeared in the January issue of CPE, Fig. 7 should have been described as a platinum-gold alloy jet.

Simultaneous Heat and Mass Transfer

Part 2

By F. Molyneux,* Ph.D., B.Sc.(Lond.), B.Sc.(Eng.), A.M.I.Mech.E., A.M.I.Chem.E.

The successful completion of the voyage of the Methane Pioneer *has focused attention on the steadily growing industrial utilisation of liquid gases. One of the problems associated with the storage and transport of these gases is the reduction of losses from tanks containing liquid gases at low temperatures. In the second part of his article the author describes a design for a vent condenser, supplied with refrigerant as a coolant and capable of reducing the liquid gas breather losses by 75%. Such a plant provides one means of reducing these losses: utilising standard longitudinal fin double-pipe heat exchanger, produced as units by many manufacturers.*

A CONDENSER having an inner pipe of 1 in. o.d. fitted with 20 × 1¼ in. fins will be used. The outer pipe will be 4-in. schedule 40 pipe. Assume an overall heat-transfer coefficient of 10 B.T.U./hr.sq.ft.°F., approximate area required =

$$\frac{2{,}264 \times 1.8}{10 \times \text{L.M.T.D.}}$$

Suppose methanol solution enters at −5°C. and leaves at −4°C., temperature difference at inlet = 5°C. and at outlet 24°C.

Log mean temperature difference =

$$\frac{24 - 5}{\log_e 4.8} = \frac{19}{\log_e 4.8} = 1.21$$

$$\therefore \text{Area} = \frac{2{,}264 \times 1.8}{10 \times 1.21} = 33.8$$

Referring to catalogue of Brown Fintube Ltd., area/ft. = 4.429

$$\therefore \text{Length required} = \frac{33.8}{4.43} = 7.64 \text{ ft., which is reasonable.}$$

Methanol flow and H.T.C.

By trial it is found that if a temperature rise of 0.589°C. is employed on the methanol solution the velocity in the inner tube is sufficient to ensure turbulent flow.

Specific heat of 30% w/w methanol = 0.93 B.T.U./lb.

$$\text{Quantity methanol required} = \frac{2{,}264}{0.93} = 2{,}420 \text{ lb./hr.}$$

Density of solution = 0.938 g./cc.

$$\text{Circulation rate required} = \frac{2{,}420}{60 \times 9.63} = 4.19 \text{ gal./min.}$$

The methanol circulation pump on the refrigeration system is capable of 75 gal./min.

Aqueous methanol is used on the *DO* plant. Its temperature varies between −5°C. and 10°C. If a line were run from this refrigerant circuit to the vent condenser it should be possible to cool the vapours leaving to at least 0°C.

V.P. *PO* at 0°C. = 180 mm. (*PO* is propylene oxide)

$$\text{Volume of air leaving condenser} = 81.7 \times \frac{273}{213} \text{ cu.ft./hr.}$$

$$\therefore \text{Weight of } PO \text{ leaving with air} = 81.7 \times \frac{273}{293} \times \frac{180}{580} \times \frac{58.1}{359} \text{ lb./hr.} = 3.83 \text{ lb./hr.}$$

$$\text{Loss of } PO \text{ would be } \frac{3.83}{16.95} \times 100 = 22.6\% \text{ at this flow rate.}$$

Symbols used in this article

A	=	Transfer area, sq.ft.
a	=	Specific surface of packing, sq.ft./cu.ft.
C_p	=	Specific heat of dry gas, B.T.U./lb.°F.
C_s	=	Humid heat, B.T.U./lb.°F.
G	=	Gas rate on dry basis, lb./hr.
h	=	Convectional heat transfer, B.T.U./hr.sq.ft.°F.
i	=	Enthalpy, B.T.U./lb.
K_g	=	Overall mass transfer coefficient, mols./hr.sq.ft.atm.
L	=	Liquid rate, lb./hr.
M	=	Molecular weight
ρ	=	Dry gas density, lb./cu.ft.
ρ_l	=	Liquid density, lb./cu.ft.
V	=	Volume of packed section, cu.ft.
λ	=	Latent heat of vaporisation of liquid, B.T.U./lb.
D	=	Diffusivity of vapour in inert gas, sq.ft./hr.
K	=	Gas conductivity, B.T.U./ft.hr.°F.
dN	=	Differential mass transfer rate, lb./mol./hr.
P	=	Total pressure (atm.)
R	=	Gas constant
T	=	Absolute temperature
μ	=	Gas viscosity, lb./ft./hr.

Senior Lecturer, Department of Chemical Engineering, Birkenhead College of Technology.

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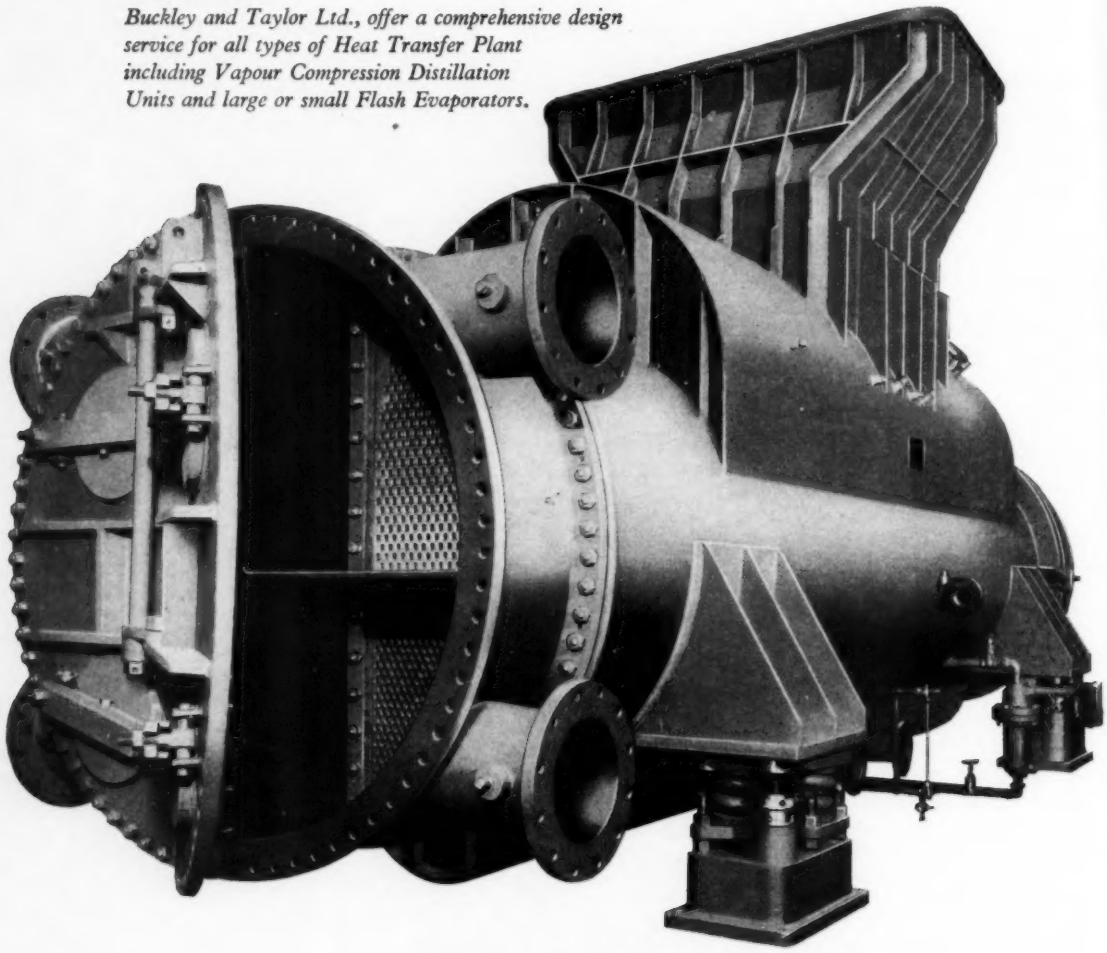

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Heat load on condenser

It will be supposed that the mean temperature of condensation is 15°C. Heat given up by gases cooling to 15°C.

$$= 16.95 \times 5 + 0.344 - 6.16 \times 5 \times 0.28$$
$$= 29.2 + 8.6 = 37.8 \text{ C.H.U./hr.}$$

Heat given up by condensation of P_o liquid
$= (16.95 - 3.83) \times 160 = 100.4$ C.H.U./hr.
Heat given up by cooling of air = 25.8 C.H.U./hr.
Total heat load = 37.8 + 1,168 + 100.4 + 25.8 = 1,332 C.H.U./hr.

Inside film coefficient

Reynolds number, $Re = \dfrac{dG}{\mu}$

At 1 in., 14-gauge tube has an i.d. of 0.834 in.
Viscosity of 30% MeOH solution at −5°C. ≏ 3.2 cp.

$$\therefore Re = \frac{2{,}420}{(\pi/4) \times (0.834/144)^2} \times \frac{0.834}{12} / 3.2 \times 2.42$$

$$= \frac{2{,}420}{0.785 \times 3.2} \times \frac{12}{0.834 \times 2.42} = 5{,}740$$

$$\frac{h}{CG} . Pr^{\frac{2}{3}} = 0.023\, Re^{-0.2}$$
$$= 0.023 \times (5{,}740)^{-0.2}$$
$$= 0.00418$$

$$Pr = \frac{c\mu}{K} = \frac{0.93 \times 3.2 \times 2.42}{0.25}$$

$$\therefore Pr^{\frac{2}{3}} = 9.40$$

$$\therefore h = 0.00418 \times \frac{0.93}{9.40} \times \frac{2{,}420}{(\pi/4) \times (0.834/12)^2}$$

$$= 0.00418 \times \frac{0.93}{9.40} \times \frac{2{,}420 \times 144}{0.785 \times 0.695}$$

$$= 264 \text{ B.T.U./hr.sq.ft.°F.}$$

Table 1. Composition of vapour at various points of condenser

Point	*Temp. °C.*	*Vapour pressure mm.*	*Mol. fraction PO*	*Molecules P_o in vapour*	*Molecules condensed*
1	20	440	0.579	0.292	0.1033
2	15	358	0.471	0.1887	0.0601
3	10	287	0.378	0.1286	0.0366
4	5	230	0.313	0.0920	0.0261
5	0	180	0.237	0.0659	

Specific heat of *PO* vapour calculated by method of Bennwitz and Rossner, specific heat of air from Perry contribution to mean specific heat assumed to be proportional to mol. faction in mixture.

Diffusion coefficient

$D_{20} = 0.1045$ sq.cm./sec. as calculated in Part I. Value corrected for temperature by assuming $D \propto T^{\frac{3}{2}}$. Viscosity of *PO* vapour calculated by Arnold's method as shown in Part 1, and viscosity of air from Perry.

Viscosity of mixture found from

$$\mu_{mix} = \frac{\Sigma \mu_i \; x_i \; \sqrt{M_i}}{\Sigma \; x_i \; \sqrt{M_i}}$$

Thermal conductivity of air from Perry. Thermal conductivity of *PO* vapour calculated from Maxwell equation: $K = E\mu C_v$

E calculated from Eucken correction expression

$$E = \frac{9\gamma - 5}{4} = 1 + \frac{4.47}{C_v}$$

This gives $K = \mu\left(C + \dfrac{2.48}{M}\right)$

Thermal conductivity of mixture calculated from Brokau equation:

$$K_m = \frac{K_1}{1 + A_{12}(x_2/x_1)} + \frac{K_2}{1 + A_{21}(x_1/x_2)}$$

A_{12} and A_{21} evaluated as follows (*Chemical Engineering Progress*, April 1957, p. 280).
Sutherland's constant for *PO*
By Rankine rule $S = 0.878\, T_c = 0.878 \times 588 = 515$°K.
By Vogel's rule $S = 1.47\, T_b = 451$°K.
By Fisher's rule $S = 0.058\, M^2 + 74 = 270$°K.
Taking average $S = 445$

$$S_{12} = 0.85\,(S_1\, S_2)^{0.5}$$
$$= 0.85 \times (412 \times 217)^{0.5} = 254\text{°K.}$$

$$a = \frac{\mu_1}{\mu_2}\left(\frac{M_1}{M_2}\right)^{0.75}\left[\frac{1 + (S_1/T_1)}{1 + (S_2/T)}\right]$$

Let 1 refer to *PO*, 2 to air.

Then at 20°C. $a = \dfrac{7.65}{1.81} \times \dfrac{1}{1.681} \times \left[\dfrac{1 + (412/213)}{1 + (217/293)}\right]$

$$= \frac{7.65}{1.81} \times \frac{1}{1.681} \times \frac{2.407}{1.741} = 3.47$$

At 0°C. $a = \dfrac{7.07}{1.71} \times \dfrac{1}{1.681} \times \dfrac{2.51}{1.8} = 3.42$

Mean value of 3.45 will be taken

$$b = \frac{1 + (S_{12}/T)}{1 + (S_1/T)} = \frac{1 + (254/283)}{1 + (445/283)}$$ taking average value of $T = 283$°K.

$$= \frac{1.866}{2.571} = 0.725$$

$$\therefore A_{12} = 0.25\,(1 + a^{\frac{1}{2}})^2 b$$
$$= 0.25\,(1 + 3.42^{\frac{1}{2}})^2 \times 0.725$$
$$= 1.49$$
$$A_{21} = 0.25\,(1 + 0.535)^2 \times 1.056$$
$$= 0.6205$$

Table 2

Point	*Temp. °C.*	*Mol.fraction PO*	*Mol.fraction Air*	*$\mu PO \times 10^{-4}p$*	*$\mu Air \times 10^{-4}p$*	*$\mu Mix \times 10^{-4}p$*
1	20	0.579	0.421	7.65	1.81	5.67
2	15	0.471	0.529	7.50	1.78	4.97
3	10	0.378	0.622	7.35	1.75	4.35
4	5	0.313	0.687	7.21	1.73	3.88
5	0	0.237	0.763	7.07	1.71	3.35

Table 3

Point	*Specific heat of PO*	*Specific heat of mixture*	*Diffusion coefficient (sq.cm./sec.) D*	*Thermal conductivity of PO (B.T.U./ft.)*	*Thermal conductivity of air*	*Thermal conductivity of mixture*
1	0.346	0.300	0.1045	0.0721	0.0149	0.0426
2	0.343	0.288	0.1019	0.0700	0.0146	0.0356
3	0.340	0.276	0.0991	0.068	0.0144	0.0301
4	0.337	0.269	0.0965	0.0663	0.0142	0.0262
5	0.334	0.261	0.0940	0.0646	0.0140	0.0231

Calculation of heat and mass transfer coefficients

Area of pipe and fins $= (\pi/4) \times 1^2 + 20 \times 1\frac{1}{4} \times 0.024$
$= 0.785 + 0.6 = 1.385$
Area of 4-in.-i.d. pipe $= (\pi/4) \times (4.026)^2 = 12.7$ sq.in.
Net area for flow $= 12.70 - 1.38 = 11.32$ sq.in.
$= 0.0787$ sq.ft.
Wetted area for heat transfer $= \pi \times 1 - 20 \times 0.024 + 20 \times 2 \times 1\frac{1}{4}$
$= 53.142 - 0.48$
$= 52.66$ in.

$$\therefore \text{Equavalent diameter} = \frac{4}{12} \times \frac{11.32}{52.66}$$
$$= 0.0716 \text{ ft.}$$

Table 4

Pt.	Vol. gas/hr. (e.f.hr.)	Velocity (ft./sec.)	Density (lb./cu.ft.)	Re	j_f	$\left(\frac{1}{P_r}\right)^{\frac{1}{3}}$	$h_f = \frac{j_f K}{D} . P_r^{\frac{1}{3}}$
1	194	0.685	0.1191	153.6	1.8	1.011	1.057
2	151.4	0.535	0.1131	130	1.7	1.011	0.834
3	126.9	0.448	0.1075	118	1.65	1.011	0.685
4	111.1	0.393	0.1035	112	1.6	1.011	0.578
5	99.8	0.352	0.1001	112	1.6	1.03	0.501

Making use of the analogy between heat and mass transfer, K_g may be calculated from

$$K_g = \frac{h}{C p_{gf}} \frac{M}{M_m} \frac{(C\mu/K)^{\frac{1}{3}}}{(\mu/\rho D)^{\frac{2}{3}}}$$

or

$$K_g p_{gf} = \frac{M}{M_m} \frac{h}{C\rho} \frac{1}{3} \left(\frac{pD}{K}\right)^{\frac{2}{3}}$$

Table 5

Point	M_m	h	$\left(\frac{\rho D}{K}\right)^{\frac{2}{3}}$	$\frac{1}{C^{\frac{2}{3}}}$	$Kg\ p_{gf}$ (lb./hr. sq.ft.)
1	46	1.057	1.02	1.492	2.035
2	42.8	0.834	1.16	1.514	1.989
3	40.1	0.685	1.234	1.535	1.880
4	38.1	0.578	1.295	1.55	1.771
5	36	0.501	1.352	1.565	1.718

Properties of finned tube

$$A_f = \frac{20 \times 2 \times 1\frac{1}{4}}{12} = 4.167 \text{ sq.ft./ft.}$$

$$A_o = \frac{\pi - 20 \times 0.024}{12} = \frac{3.142 - 0.48}{12} = \frac{2.662}{12}$$
$$= 0.222 \text{ sq.ft./ft.}$$

$A_t = 0.2183$ sq.ft./ft. (Kern)
Fin efficiency is defined as $\Omega = \tan mb/mb$

where $m = \left(\frac{P}{K a_x}\right)^{\frac{1}{2}} h_f^{\frac{1}{2}}$

P = fin perimeter, ft./ft.
K = thermal conductivity of metal
a_x = c.s. a of fin/ft.

$$\therefore m = \left(\frac{2 \times 1}{K \times 1 \times t}\right)^{\frac{1}{2}} h_f^{\frac{1}{2}} \quad \text{where } t = \text{thickness}$$
$$= \left(\frac{2}{Kt}\right)^{\frac{1}{2}} h_f^{\frac{1}{2}}$$

For fins 0.024 in. thick
$K = 9.2$ B.T.U./hr.sq.ft.°F./ft.

$$m = \left[\frac{2}{9.2 \times (0.024/12)}\right]^{\frac{1}{2}} h_f^{\frac{1}{2}} = \frac{h_f^{\frac{1}{2}}}{0.09595}$$

$$mb = \frac{h_f^{\frac{1}{2}}}{0.09595} \times \frac{S}{48} = 1.088\ h_f^{\frac{1}{2}}$$

Thus Table 6 drawn up:

Table 6

h_f	mb	$\tan mb$
0.305	0.6	0.5374
0.541	0.8	0.664
0.850	1.0	0.7615
1.43	1.3	0.862
2.06	1.6	0.922
3.39	2.0	0.964
5.30	2.5	0.987
7.61	3.0	0.995
10.38	3.5	0.998
13.55	4.0	0.999
17.2	4.5	0.999
21.1	5.0	1
25.6	5.5	1
30.5	6.0	1

Variation of vapour pressure of P_o with temperature

The driving force in some parts of the condenser, the difference between the vapour pressure of P_o in the gas and at the interface, is so small that it is not sufficiently accurate to get the value from plots of vapour pressure against temperature. Instead, an analytical expression for the variation of vapour pressure with temperature over the range considered must be used, and this must first be derived.

Assuming that vapour pressure of P_o is represented by:

$$\log_{10} p = \frac{-A}{T + 230} + B$$

Then if p_1 and p_2 are the vapour pressures at two temperatures T_1 and T_2

$$\log_{10} \frac{p_2}{p_1} = \frac{A}{T_1 + 230} - \frac{A}{T_2 + 230}$$
$$= \frac{A(T_2 - T_1)}{(T_1 + 230)(T_2 + 230)}$$

According to Perry, vapour pressure at −12°C. = 100 mm.
17.8°C. = 400 mm.

$$\therefore \log_{10} \frac{400}{100} = \frac{A(17.8 + 12)}{247.8 \times 218}$$

$$\therefore A = 0.6021 \times \frac{247.8 \times 218}{29.8} = 1{,}091$$

$$\log_{10} \frac{p}{100} = 1{,}091 \left(\frac{1}{218} - \frac{1}{T + 230}\right)$$

Point-to-point calculation

Calculation is simplified by ignoring the existence of the film of condensed liquid (negligible). The dirt film will also be very small and may be ignored. The method of procedure is to take some trial interface temperature, calculate the heat flux and then see whether the two temperatures drop (gas film-tube side liquid film) add up to the temperature difference between the vapour and liquid.

Point 1 will be calculated to illustrate the method.

First, vapour pressure at 20°C. must be accurately calculated.

$$\log_{10}\frac{p}{100} = 1{,}091\left(\frac{1}{218} - \frac{1}{250}\right)$$

$$= \frac{1{,}091 \times 32}{218 \times 250} = 0.6404 = 436.9 \text{ mm.}$$

Assume interface temperature of 2.7°C.
Vapour pressure at 2.7°C.

$$\log_{10}\frac{p}{100} = 1{,}091\left(\frac{1}{218} - \frac{1}{232.7}\right)$$

$$= \frac{1{,}091 \times 14.7}{218 \times 232.7} = 0.3161$$

$$p = 207 \text{ mm.}$$
$$\therefore \Delta p = 436.9 - 207 = 229.9$$
$$p_{gf} = 760 - \frac{437 + 207}{2} = 760 - 322 = 438$$

$$\therefore \text{Rate of mass transfer} = 2.035 \times \frac{229.9}{438} \text{ lb./hr.sq.ft.}$$

$$\therefore \text{Rate of heat transfer} = 2.035 \times \frac{229.9}{438} \times 160 \text{ B.T.U./hr./sq.ft.}$$

Since Δt over gas film $= 17.3 \times 1.8$, this is equivalent to a film coefficient of:

$$2.035 \times \frac{229.9}{438} \times \frac{160}{17.3 \times 1.8} = 5.48$$

Gas film coefficient is 1.057
$\therefore$ combined coefficient is $5.48 + 1.06 = 6.54$
$mb = 1.088 \times (6.54)^{\frac{1}{2}} = 2.8$
$\tan mb = 0.992$

$$\therefore \quad \Omega = 0.344 = \frac{\tan mb}{mb}$$

$$h_{fi} = \frac{(\Omega A_f + A_o)h_f}{A_i} = \frac{(0.344 \times 4.167 + 0.222)h_f}{0.2183}$$

$$= \frac{(1.468 + 0.222)h_f}{0.2183} = \frac{1.690\ h_f}{0.2183}$$

$$= \frac{1.690}{0.2183} \times 6.54 = 50.5$$

Liquid methanol is at -4.4°C.
$\therefore$ Proportion of Δt over methanol film

$$= \frac{50.5}{264 - 50.5} \times 24.4$$

$$= \frac{50.5}{314.5} \times 24.4 = 3.9\text{°C.}$$

$\therefore$ better value for interface temperature would have been:

$$-4.4 + 3.9 = -0.5\text{°C.}$$

Second trial

Vapour pressure at -0.5°C.

$$\log_{10}\frac{p}{100} = 1{,}091\left(\frac{1}{218} - \frac{1}{229.5}\right)$$

$$= \frac{1{,}091 \times 11.5}{218 \times 229.5} = 0.2507$$

$$p = 178.1 \text{ mm.}$$
$$p_{gf} = 452 \text{ mm.}$$

$$\Delta p = 436.9 - 178.1 = 258.8$$

$$\therefore \text{equivalent film coefficient} = 2.035 \times \frac{258.8}{452} \times \frac{160}{20.5 \times 1.8}$$

$$= 5.05$$

Net film coefficient $= 5.05 + 1.06 = 6.11$
$\therefore$ $mb = 1.088 \times (6.11)^{\frac{1}{2}} = 2.69$
$\tan mb = 0.990$
$\Omega = 0.368$

$$h_{fi} = \frac{(\Omega A_f - A_o)h_f}{A_i}$$

$$= \frac{(0.368 \times 4.167 + 0.222)}{0.2183} \times 6.11$$

$$= \frac{(1.531 + 0.222)}{0.2183} \times 6.11 = 49.0$$

Δt over liquid film $= \frac{49}{264 + 49} \times 24.4$

$$= \frac{49}{313} \times 24.4 = 3.8\text{°C.}$$

$\therefore$ better approximation for interface temperature would have been -0.6°C.

Vapour pressure at 0.6°C. $\log_{10}\frac{p}{100} = 1{,}091\left(\frac{1}{218} - \frac{1}{229.4}\right)$

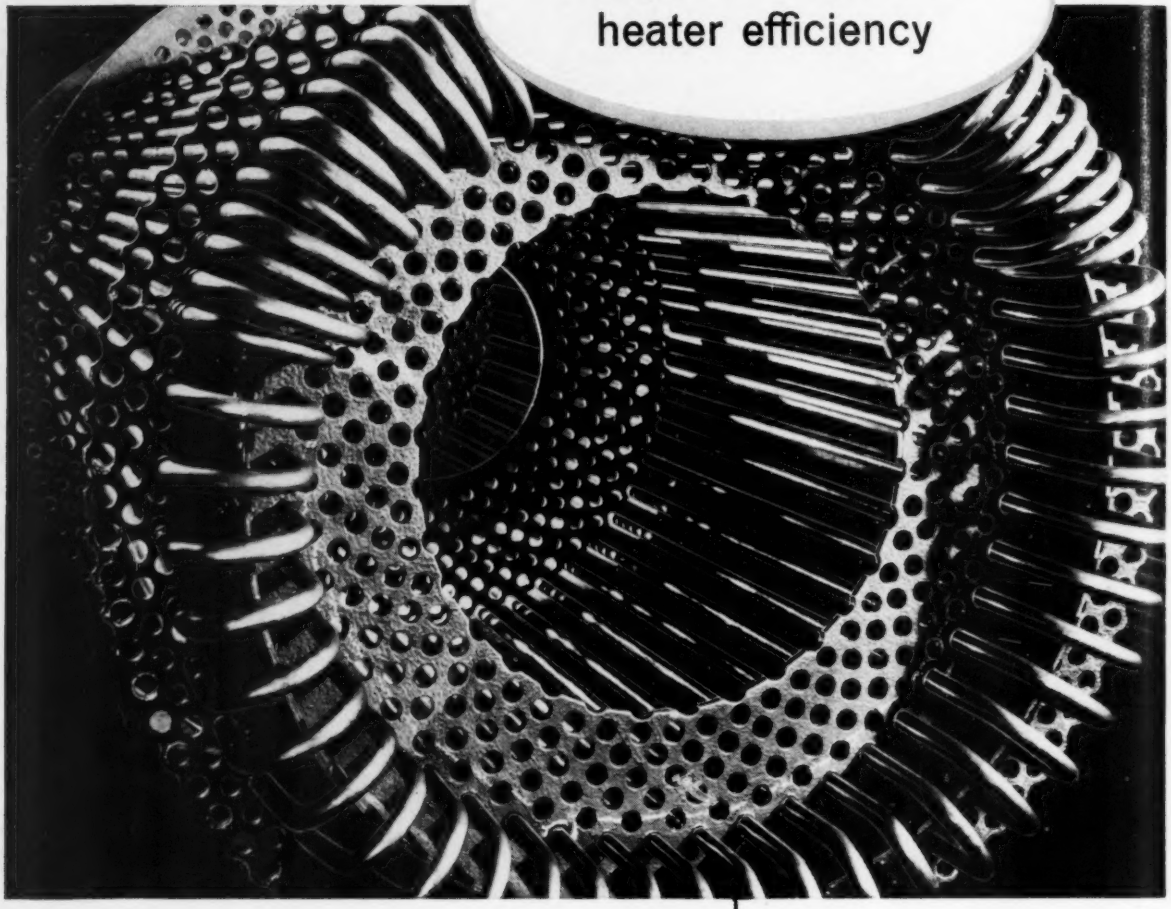
$$\log_{10}\frac{p}{100} = \frac{1{,}091 \times 11.4}{218 \times 229.4} = 0.2486$$

$$p = 177.2 \text{ mm.}$$

Table 7

	Pt. 1	*Pt.* 2	*Pt.* 3	*Pt.* 4	*Pt.* 5
Gas temperature, °C.	20	15	10	5	0
Methanol temperature, °C.	-4.4	-4.65	-4.8	-4.92	-5.0
Interface temperature, °C.	-0.6	-1.9	-2.98	-3.84	-4.5
Vapour pressure *PO* in vapour in mass	436.9	355.9	287.5	230.1	182.4
Vapour pressure *PO* at interface	177.2	165.9	158.1	151.6	146.7
Δp mm.	259.7	190	129.4	78.5	35.7
p_{gf} mm.	453	499	537	569	595
Equivalent h_f for heat transfer by condensation F. units	5.025	3.98	3.102	2.462	2.037
Total vapour film coefficient	6.08	4.815	3.787	3.04	2.538
mb	2.68	2.386	2.116	1.893	1.731
$\tan mb$	0.990	0.982	0.969	0.953	0.936
Ω	0.369	0.411	0.458	0.503	0.540
Film coefficient referred to pipe i.d. h_{fi}	49.25	42.6	36.95	32.38	28.62
Proportion temperature drop across film $\frac{h_{fi}}{h_{fi} \times h_i} \times \Delta t$	3.84	2.74	1.815	1.08	0.49
Heat flux B.T.U./ft.hr.°F.	399	283.5	187	112.2	28.2
$\frac{1}{F} \times 10^{-3}$	2.506	3.528	5.348	8.89	35.46
Heat transferred so far	0	1,035	1,682	2,095	2,400

Design for feedwater heater efficiency



This partially assembled feedwater heater nest is designed to accept steam at 800 F and it incorporates 30,000 feet of solid drawn steel tube.

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$$\Delta p = 436.9 - 177.2 = 259.7$$
$$p_{gf} = 453 \text{ mm.}$$

$$\text{Equivalent film coefficient} = 2.035 \times \frac{259.7}{453} \times \frac{160}{20.6 \times 1.8}$$
$$= 5.025$$
$$\therefore \text{Net film coefficient} = 6.08$$
$$\therefore mb = 2.68$$
$$\Omega = 0.369$$
$$A_t h_{ft} = (\Omega A_f - A_o)\, h_f$$
$$= (0.369 \times 4.167 + 0.222) \times 6.11$$
$$= (1.538 + 0.222) \times 6.11$$
$$= 10.77$$
$$\therefore \text{Heat flux} = 10.77 \times 20.6 \times 1.8$$
$$= 399 \text{ B.T.U./ft.}$$

Let F be the heat flux per unit length B.T.U./hr.ft.
Q = heat transferred B.T.U./hr.
l = length of condenser tube

$$\text{Then } \frac{\delta Q}{\delta l} = F \qquad \therefore \delta L = \frac{\delta Q}{F}$$

$$\therefore \int \delta l = \int \frac{\delta Q}{F}$$

$$l = \int_0^Q \frac{\delta Q}{F}$$

If a graph of l/F is plotted against heat transferred Q the area will give the length of condenser tube required. This graph has been plotted, and its area is 33.86 sq.cm. and each sq.cm. represents $2 \times 10^{-3} \times 200$ sq.ft. $= 0.4$ ft. Therefore, length of tube required $= 33.86 \times 0.4 = 13.55$.

A condenser 14 ft. long would be required. This would a rather inconveniently long length. If the fin efficiency was improved by using thicker fins a shorter condenser would result. A condenser will therefore be designed having fins 0.0625 in. thick. This gives a new length of condenser of 9.69, say 10 ft.

Because of the low temperatures at which the unit operates, the lagging recommended is either cork or one of the special foamed plastics which have proved so successful in refrigeration practice.

Acknowledgment is made to Mr. L. R. Cox, B.SC., A.M.I.CHEM.E., of the department of chemical engineering, who was responsible for the condenser design calculations.

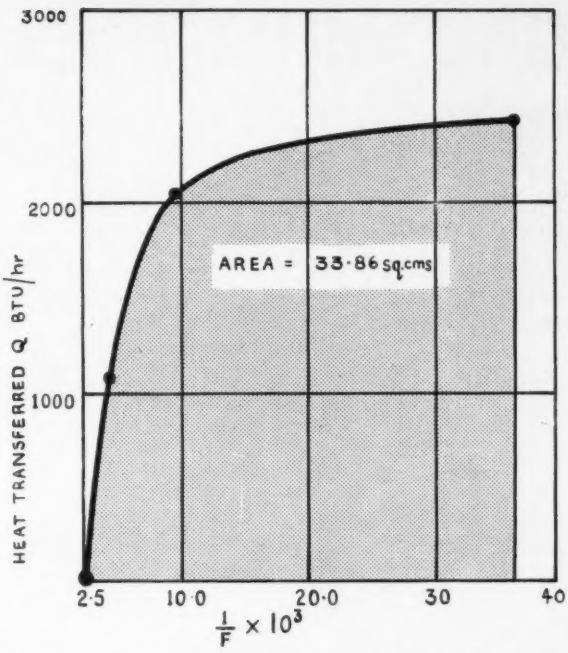

Fig. 1 shows the length of condenser tube required, obtained by plotting l/F against heat transferred

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Accelerated freeze drying

One of the most important techniques developed since the end of the war has been freeze drying, especially its applications in the food and pharmaceutical industry. In the February issue of **Food Manufacture** a special feature will deal with accelerated freeze drying including articles contributed by leading experts in this field. Other articles in the journal will be: Factory Visit to Spillers' Flour Mills at Silvertown and Annual Reviews on the Baking Industry and Brewing Industry.

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Manufacturing Chemist — Special feature on packaging materials and machinery. Evans Vaccine Plant at Speke. Gelatin Capsule Manufacture, by G. Muller. The Paul Ehrlich Institute at Frankfurt, by G. Eisner. Carbohydrates in the Chemical Industry—2, by G. Machell.

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CHURCHILL COLLEGE, CAMBRIDGE

By J. A. Oriel, C.B.E., M.C., M.A., M.I.Chem.E.

Churchill College, Cambridge, which was recently opened, represents a completely new departure in British higher education. For the first time one of the ancient universities has established a college, the majority of whose students and Fellows are engaged in science and technology. The author, a past-president of the Institution of Chemical Engineers and a Fellow Extraordinary of Churchill College, describes the structure and discusses the scope and importance of this new college.

LAST October, at the commencement of the Michaelmas term, 1960, a new college was opened at Cambridge—the first to be established for well over a century. The college is named Churchill College after that illustrious Englishman and as a memorial of the great work he has done for this country. The college has, in addition, several special features which are naturally related to the times in which we live. There is, as we all know, a great need for a change in the educational requirements of our country. In 1955 many industrialists, realising the urgency of this situation, combined together to establish a fund for the provision of facilities for teaching science and mathematics in the public schools. At the same time those reading science and mathematics in the grammar schools increased considerably with the result that the number reading science and mathematics at our secondary schools has increased to the point where the scientists leaving the sixth forms have now reached about 60%.

This, in itself, is a revolution and universities have to adapt their intake to cope with this increased flow. At the same time we should not allow ourselves to be forced into altering our educational system so as to compare ourselves in any way with other countries whose educational systems are, and always have been, entirely different. It is far better that we should adapt and shape our well-tried educational framework to meet the modern need.

The founders of Churchill College are anxious that it should reflect the character of its eponym in displaying a dynamic approach, whilst at the same time remaining ever conscious of a sense of history. They intend to continue as far as they are able to produce the 'educated man' in the typical British way. In 1958 the next step took place to follow the development in the schools, and the sponsors decided to establish this college at Cambridge within the framework of the university and its educational system, incorporating the new features already mentioned.

The whole idea struck an imaginative note and funds were rapidly collected and many people were not only willing but anxious to contribute with materials and ideas. The trustees of the fund were men of industry, both employers and trade unionists, and also senior members of the University of Cambridge who have given unsparingly of their time to assist in the development of this new college. The chairman of the trustee committee was Sir Winston himself.

Gifts poured in from all sides; materials for the buildings are being provided by almost all the Commonwealth countries; the Isaac Wolfson Trust donated funds for the assembly hall which is to be named after him; similarly named after the men concerned are the reading room, given by friends of Lord Bracken from funds collected in his memory, and the library which is being established with funds provided by the Transport and General Workers Union in memory of Ernest Bevin. Many of the gifts are works of art and are contributions to the aesthetic life of the college. From all this it is clear that the interest in this new college transcends all political parties and divisions. It is concerned solely with the development of a college to meet the modern need.

Total population

The total population of the college will eventually be 600—Fellows and students—and when the buildings are complete it will be fully residential. Of these 600 Fellows and students, about 70% will be concerned with the sciences and technologies whilst 30% will be concerned with the arts and humanities. Of the student population one-third will be concerned with postgraduate work. This is an important and novel feature of the college. Some of the postgraduate students will, of course, be carrying out research in the traditional university manner, whilst others—it is hoped about half the postgraduate population—will be provided with courses of instruction at postgraduate level each in his own subject. These postgraduate courses will be open not only to graduate members of the college but also to those of other colleges and other universities. This interest in postgraduate instruction as well as postgraduate research is something to which the college is giving particular attention. At the same time, it is pleasant to note that the university departments are giving this aspect considerable encouragement.

The academic aims of the college are clearly shown by the names of those who have been chosen to take part in its government and teaching. Its first master is Sir John Cockcroft, O.M. He is recognised throughout the world as one of the greatest modern nuclear physicists who has dedicated his life to this subject ever since his undergraduate and postgraduate researches associated with Sir J. J. Thompson and Lord Rutherford. This in itself is an example of the approach to modern science which the

Model of Churchill College architect's plans

college intends to adopt. Similarly, the 60 Fellows who will eventually make up the teaching staff are men of all ages who have taken part and are now taking part in the development of their own particular subject. There is a senior tutor for undergraduates and a senior tutor for postgraduate students. Not only is the teaching staff of the college itself of the highest calibre, but it is to be supplemented by a special arrangement whereby notable professors and others from other countries will be invited from time to time to become resident fellows of the college for a period of a year or for such time as they can find convenient. In this way there will permanently be some five or more Fellows from other countries resident at the college. Among these will be men famous throughout the world for their work in the sciences, technologies and the arts.

Men from industry

Arrangements are also being made to accept for short periods men from industry. These men are intended to be in residence at the college during the period of their courses and it is hoped that industry will take advantage of this arrangement whereby lectures and courses will be available either at the College or in the departments of the university. These courses are intended for men who are clearly making their way in industry and who will benefit from college residence, university lectures and college tutorials. These courses have two purposes, to refresh the memory of those graduates who have been in industry for some little time and to instruct them in the new developments which have occurred since their graduate days.

As already mentioned, there will be 30% of the population concerned with the humanities. The student population on this side will be treated in exactly the same way as those reading the sciences. It is anticipated that they will, in fact, benefit greatly from being resident in a college where the majority of work is devoted to the modern outlook and who knows what influence this preponderance of science may have on some future prime minister, even if it is still necessary to choose him from the ranks of those who have been students of the humanities.

For those who fear that the college is overlooking sport it should be added that there is adequate provision for playing fields in the precincts of the college itself and, again in the modern outlook, it is intended to establish an ice rink and a swimming pool where who knows what applied science will be put to use to warm the swimming pool by cooling the ice rink. When these facilities are installed it is hoped that to some extent they may be open to members of other colleges in the university. The traditional Cambridge rowing has not been forgotten and, in the meantime, it is hoped that accommodation at a boathouse will be available by the courtesy of one of the other colleges.

This short account will give some idea of how the sponsors of Churchill hope to develop the new approach to education—whilst the arts take their rightful place, the preponderance of the population will be concerned with the sciences, both pure and applied. The applied side will receive as much attention as the pure side of the sciences and the college recognises and wishes to develop the importance of the technological aspect of science and the dependence of the pure and applied on each other, for where would Gallileo have been without the lens polisher or, as the president of the British Association said recently, where would our pure physicists be today without the work of the technologist producing and maintaining for him the high vacuum upon which he so much depends.

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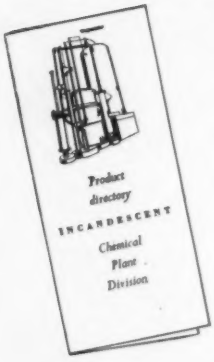

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EVAPORATION

By P. J. King,* B.Sc., Ph.D.

This review on recent trends in evaporator design describes the more important developments in evaporation during the last three years. Significant investigations concerning the resistance to boiling heat transfer in tubes have resulted in the design of the agitated thin film evaporator. This and other novel types of evaporators are critically reviewed by the author.

As in a previous review on evaporators[1] the field of reference has been restricted to evaporators of particular interest in the fine chemicals industry; in general this has been taken to mean evaporators to handle comparatively valuable and/or heat-sensitive materials. Less attention has been paid to heat (steam) economy, improved efficiency and scale formation than to the four requirements listed below:

(*a*) Low absolute temperature of the liquor.
(*b*) Low temperature difference between the heating medium and the liquor.
(*c*) Short time of residence.
(*d*) Minimum loss by entrainment.

The main headings under which the work will be discussed are research, new and improved design and selection of equipment, design and economics.

Research

Published work in this field during the past few years has been almost entirely concerned with the climbing-film evaporator. This apparatus is well known to the chemical industry, having first appeared commercially in the early years of this century. However, since the war much effort has been involved in research designed to extend the usefulness of the apparatus, especially to heat-sensitive materials, and to lead to an understanding of the fundamentals of its operation. Descriptions of commercial apparatus using this principle will be found in most unit operations textbooks.[2]

In 1956, Whitt[3] studied the performance of three sizes of climbing-film evaporators, evaporating organic liquids with Prandtl numbers of between two and three and with viscosities of about 0.3 centipoise. Hot-water heating was used and the evaporator tubes were made of silver. A constant L/D ratio was employed, with tube sizes of $\frac{1}{2}$ in. by 5.17 ft., $\frac{3}{4}$ in. by 7.5 ft. and 2 in. by 20 ft. Temperature difference was in the range 8.5° to 41.5°C.

Under these conditions there was little effect of solution concentration on the rate of evaporation, and almost complete evaporation was obtained for all dilutions used. However, there was evidence for the existence of a critical temperature difference between the heating medium and the vaporising liquid. This resulted in a falling off of the overall heat-transfer coefficient (U) in a maximum value of heat flux of about 12,000 B.T.U./(sq.ft.)(hr.) and with a critical film temperature difference of about 20°F. Up to this value of critical temperature difference, the heat flux (Q) increased with temperature difference (ΔT) and could be represented by:

$$Q/A = 100\Delta T^{1.25} \text{ B.T.U./(sq.ft.)(hr.)} \quad (\Delta T \text{ in °F.}) \quad \ldots\ldots\ldots (1)$$

On the basis of the experiments it was concluded that the design methods proposed by Kern[4] for natural-circulation evaporators could be applied to the design of climbing-film evaporators. Later the same year Lee, Dorsey, Moore and Mayfield[5] published additional information for natural-circulation (thermosiphon) evaporators obtained for a variety of liquids at various pressures, the data being successfully correlated. The liquids investigated included water, acetone, propylene glycol, *n*-propanol, ethyl toluene, benzene and *n*-butane, and pressures ranged from 0.1 to 10 atm.

Cathro and Tait[6] in 1957 made a detailed investigaton of the boiling action inside a climbing-film evaporator. They investigated eight liquids boiling inside four different tubes and they correlated their experimental data, together with much of the published data by equation (2). This equation was obtained by the process of dimensional analysis:

$$\frac{(h_b D/k)}{(DG/\mu)^{0.25}(D\rho_L\lambda\mathcal{J}/\sigma)^{0.48}(L/D)^{0.7}(D/K)^{0.5}} = \varphi\left(\frac{\Delta t_b C}{\lambda}\right) \quad \ldots\ldots\ldots\ldots (2)$$

NOMENCLATURE

A	=	Area
C	=	Specific heat
D	=	Tube diameter
g	=	Acceleration due to gravity
G	=	Mass flow rate
h	=	Height of evaporation area
h_b	=	Boiling film coefficient of heat transfer
$\mathcal{J}$	=	Conversion factor (718 ft.lb. = 1 B.T.U.)
k	=	Thermal conductivity
K	=	A constant ($\frac{1}{32}$ if D is in ft.)
K_o	=	A constant
L	=	Tube length
n	=	An exponent
N	=	R.p.m. of motor
p	=	A constant
P	=	Power requirements
Q	=	Heat flux
r_1	=	Radius of rotor blades
r_o	=	Radius of rotor shaft
R	=	Resistance to heat transfer
t_2	=	Clearance between rotor blade tip and tube wall
U	=	Overall coefficient of heat transfer
w_f	=	Mass flow of feed
x_o	=	Concentration of solution at tube entry
Δt	=	Temperature difference
Δt_b	=	Boiling film temperature difference
λ	=	Latent heat
μ	=	Viscosity
ρ_L	=	Density of liquid
σ	=	Surface tension
ω	=	Rotor angular velocity
φ	=	Some function

*Department of Chemical Engineering, Fuel Technology and Metallurgy, the Manchester College of Science and Technology.

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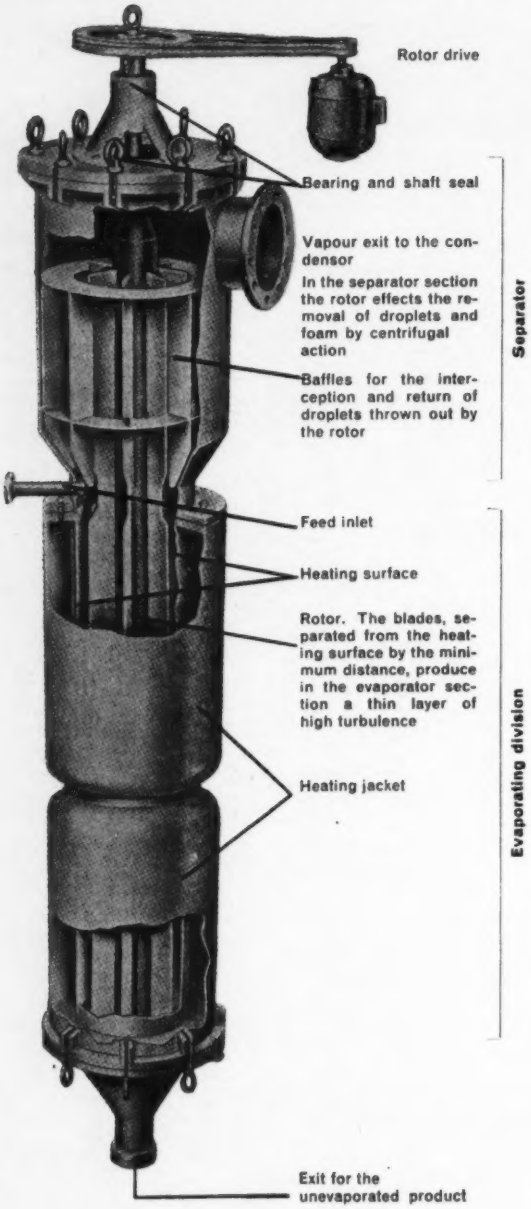
Rotor drive
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In the experimental work reported in the paper the following variations in the various dimensionless groups were made:

$(\Delta t_b C/\lambda)$ 30 : 1 $(D\rho_L\lambda\mathcal{J}/\sigma)$ 3 : 1
$(h_b D/k)$ 30 : 1 $(L/D) = 2 : 1$
(DG/μ) 25 : 1 $(D/K) = 2 : 1$

Most of the above groupings are readily recognisable. The group $(\Delta t_b C/\lambda)$ is significant in problems concerned both with condensation of vapour and with film boiling; it expresses the ratio of the superheat in the liquid film to the total heat transferred. The group $(D\rho_L\lambda\mathcal{J}/\sigma)$ is the ratio of the mechanical and the thermal energy required to produce new surface.

The exponent of 0.25 on the $N_{Re}(DG/\mu)$ in equation (2) was only applicable above a certain critical value, but with this limitation the equation correlated available data to within $\pm 30\%$. However, it was reported to be only applicable to pure liquids or perhaps to small degrees of concentration. With more concentration it was suggested that equation (3) should be used. This equation was developed by taking mass and enthalpy balances over a differential section of the column and integrating the result:

$$Q + (\lambda p W_f x_o)\left[ln\frac{W_f(1 - px_o)}{(W_f[1 - px_o] - Q/\lambda)}\right] = K_o A \Delta t_b^{n+1} \quad \ldots\ldots\ldots (3)$$

Dengler and Addoms[7] studied the heat-transfer mechanism for the vaporisation of water in a 20 ft. by 1 in. vertical copper tube. They concluded that: (1) the mechanism was primarily convective (nucleate boiling was dominant only under conditions of low liquid velocity and was gradually depressed by the effects of vapour velocity which induced forced convection); and (2) the operating variables exerted an independent and often contradictory effect on each of these mechanisms, for example:

(*a*) Increase of pressure may have increased the heat-transfer coefficient, because it increased nucleate boiling, or it may have decreased the coefficient, in the range of two-phase convection, by having raised the average gas density and hence lowered the velocity.

(*b*) Increase in temperature difference promoted nucleate boiling but had no direct effect on convectional coefficients.

(*c*) Increase in total mass throughput increased the convectional heat transfer, but decreased nucleate boiling heat transfer by lowering the available effective temperature driving force for nucleation.

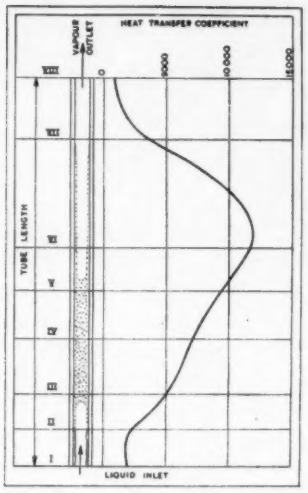

Fig. 1. Variation in heat transfer coefficient over tube length[10]

1 Heating section 2 Boiling section
3 Emulsion section 4 Plug flow
5 and 6 Annular flow 7 Wet steam
8 Saturated steam

In 1958, Pepper[8] made a fairly complete assessment of available published data on climbing-film evaporators and analysed the factors which should be important for the design of equipment. The general conclusion arrived at was that it was possible to design climbing-film evaporators from available data for aqueous or similar solutions if tube diameters were less than 1 in., but for larger tubes or for different liquids it was necessary to extrapolate data (some of the difficulties could be overcome by redesign in order to use a multiple of smaller tubes).

On the basis of this assessment, evaporators had been designed for the A.E.R.E. and were reported to have come up to design performance; an example was given of a $\frac{13}{16}$-in. 8-ft. nickel tube heated by steam. The design was to handle 750 ml./min. of dilute sodium hydroxide solution to give 375 ml./min. of concentrate. The designed value for the overall heat-transfer coefficient was 548 B.T.U./(sq.ft.)(hr.)(°F.) and the actual value was found to be 516 B.T.U./(sq.ft.)(hr.)(°F.).

Also in 1958, Doll-Steinberg[9] published the results of an investigation into the performance of two *Monel* metal tubes 95 cm. long (one 1.13 cm. i.d., 1.17 cm. o.d., and the other 0.735 cm. i.d., 0.77 cm. o.d.). The investigation covered such factors as the effect of liquid submergence and temperature difference on the water circulation rate and on the heat-transfer coefficient. The results were expressed graphically; in general it was found that below a certain value of temperature difference, which was greater at higher submergences, the heat-transfer coefficient varied as $\Delta t^{0.3}$ (Δt in °C.). There followed a region where the exponent on the temperature difference became greater, the actual value (which was reported to vary between 0.6 and 0.95) depended both on submergence and on tube diameter. Finally, at higher values of Δt, a falling off of the coefficient was reported. This maximum value is in line with other workers who have reported the existence of a critical temperature difference.[3] A qualitative explanation of these results was made in terms of the superheating of, and bubble formation in, the boundary layer.

Liquid circulation rate

Similar results were reported for the effect of Δt on the liquid circulation rate. In this case four regions were reported. As Δt increased from a low value, there was a rapid rise in circulation to a maximum value, where it remained almost constant. (At high submergences in the large tube this maximum value extended over a wide range of Δt, but at low submergences in the small tube the maximum value only extended over a small range of Δt). The rate then fell off almost linearly with intermediate values of Δt and finally attained an almost constant or slightly decreasing rate at high values of Δt. These results were also explained qualitatively, in this case in terms of 'slip' between the vapour and liquid.

Recent Soviet research has been reported by Jackson.[10] It is stated that Tobilevich and Shchegolev[11] investigated the overall resistance to heat transfer in a climbing-film evaporator and divided the overall resistance into the usual individual resistances, *e.g.* equation (4):

$$R = R_1 + R_W + R_d + R_2 \quad .. (4)$$

where R_1 is the resistance for the condensing steam, R_W is the resistance of the tube wall, R_d is the resistance of the dirt layer and R_2 is the resistance of the boiling liquid.

The data for a number of evaporators (for which no details were given) were reported to show the relationship expressed in Table 1.

Table 1.[16] Relationship between individual and overall resistances for various effects

Resistance	Proportion of overall resistance (%)			
	First effect	Second effect	Third effect	Fourth effect
R_1	20	10	6	4
R_w	5	4	3	1
R_d	30	36	31	25
R_2	45	50	60	70

Hence it would appear that the most useful reductions would be to resistances R_d and R_2. Fig. 1 shows the variation in heat-transfer coefficient with tube height. In general, there were portions of the tube (the boiling section) where heat-transfer rate was high, and other portions where it was very low (the heating section at the base and the upper part of the tube where there was much vapour). The proportions of the tube length occupied by each section was found to depend on circulation velocity. For example, at low circulation rates the heating section was small, but the section containing boiling liquid with a high vapour content was large and above this there was a section containing virtually wet steam, hence the overall coefficient of heat transfer was small. As circulation rate rose, the section containing a high proportion of vapour decreased, but the preheating section became larger.

New and improved design

The data in Table 1 show that the greatest resistance to heat transfer for liquid boiling inside tubes lies in the liquid film. It is not suprising, therefore, that a number of evaporators proposed or modified during the past few years have incorporated devices designed to reduce this resistance.

Table 2.[15] Values of overall resistance reported by Gudheim and Donovan

Substance	U (B.T.U.)/(hr.)(sq. ft.)(°F.)
Acetic acid	745
Fatty acids	330
Isopropyl alcohol ..	400
Methyl alcohol ..	650
Water	700

The general solution[12–15] has been to place a rotor inside the evaporator tube and to attach wipers to this rotor. This device has been applied to both falling- and climbing-film evaporators. Without mechanical aid the film (particularly the falling film) tends to be unstable and dry spots develop on the heated tube wall. To avoid this and also to provide agitation of the liquid film, wipers or blades are attached to a rotor arranged concentrically inside the tube. These wipers may either be arranged to just clear the tube wall, to give a fixed film thickness of 1 to 2 mm., as in Fig. 2 (*a*), or may be hinged so as to press on the tube wall by centrifugal force (possibly supported by the addition of springs) as in Fig. 2 (*b*) and Fig. 5. In this case the film thickness is controlled by a balance between the pressure exerted by the blades and the resistance caused by the viscosity of the liquid.

In 1957, Gudheim and Donovan[15] described three types of evaporator (Fig. 3) which utilised the agitated thin film principle of heat transfer. In each of these, rotating blades turned inside a cylinder or truncated cone, developed a centrifugal force in the process liquor, and caused a violently agitated film to form on the circular wall. The holdup was reported to be small and, by suitable control of feed rate, etc., residence time could be reduced to a few seconds. The effect of feed rate variations and the use of vacuum was discussed and Table 2 shows some of the data reported for overall heat-transfer coefficient. It was claimed that this type of evaporator would give liquid side coefficients of the same order as for the steam side.

A detailed investigation of this type of unit was made in 1959 by Lustenader, Richter and Neugebauer.[16] The evaporator used was a vapour compression unit, where the evaporated liquid (water vapour) was compressed and used to provide heat for further evaporation. The apparatus consisted of a copper tube 24 in. long and 3 in. diam. with a wall thickness of 0.035 in. The outer annulus (heating jacket) was provided with transparent walls so that the condensation of the heating vapour could be studied. The investigation was carried out with low values of temperature difference and it was assumed that under these conditions there would be no bubble formation. Three conditions were postulated as shown in Fig. 4.

Condition

(*a*) would occur at low wiper speeds, when dry spots would be formed before the wiper could redistribute the film. In this case only a portion of the surface would be utilised.

(*b*) would occur with increase in rotor speed and represents the state at which all the surface was just wetted all the time.

(*c*) at higher speeds there was an increase in average film thickness (the limit is an infinite speed for the wiper and a constant film thickness).

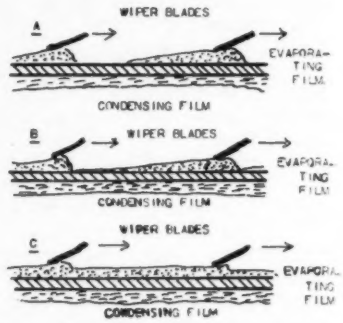

Fig. 4. Film flow in agitated evaporators[16]: (a) low wiper speed; (b) intermediate wiper speed; (c) high wiper speed

Each case was analysed and it was shown that the maximum heat was transferred under condition (*b*). It was also reported that the temperature difference and the wiper speed had no influence on the magnitude of the maximum or minimum value of the overall heat-transfer coefficient; this was determined by the initial film thickness and the condensing side heat-transfer coefficient. In an investigation into the importance of the condensing side coefficient, it was shown that a grooved or fluted surface gave a much higher value of heat transfer than a smooth polished surface. They obtained a maximum value of overall transfer coefficient of 8,300

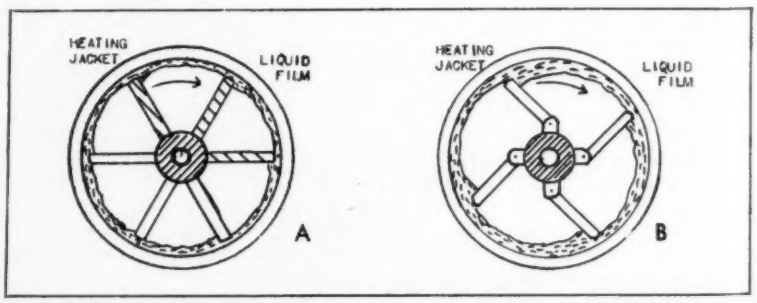

Fig. 2. Agitated thin film evaporators[12] A.—Fixed blade B.—Hinged blade

B.T.U./(sq.ft.)(hr.)(°F.) and the tests indicated that the fluted surface had an average condensing coefficient of about 10,000 B.T.U./(sq.ft.)(hr.)(°F.) at an overall Δt of 1.5°F. (this is four times larger than would be expected for a smooth surface of the same dimensions). They used several different types of wiper design, but the final version is shown in Fig. 5. The brushes are of carbon with bronze screening as the back-up springs.

Hadley and Thomas[17] recently published a mathematical and experimental study of the agitated thin film evaporator. The experimental apparatus closely resembled that described by Haley.[13] Equation (5) was developed for the critical angular velocity (ω_o) below which a portion of the evaporator tube became filled with liquid:

$$\omega_{o^2} = \sqrt{\frac{2gh}{(r_1^2 - r_o^2)}} \quad \ldots\ldots\ldots (5)$$

Equations were developed and confirmed experimentally for the volume holdup with angular velocities both above and below the critical. The power requirement (in h.p.) for this type of evaporator was given by equation (6):

$$P = 0.263 \times 10^{-8}\left(\frac{hr_1^3}{t_2}\right)N^2\mu \quad \ldots (6)$$

It was observed that any design of this type must be a compromise between high-volume holdup and resi-

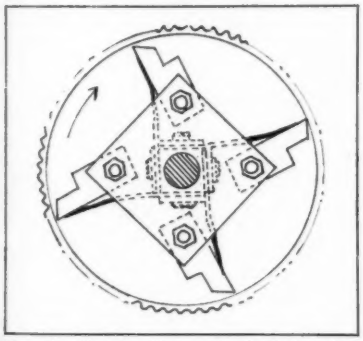

Fig. 5. Sketch of a spring-loaded carbon wiper assembly[16]

dence time, and high power requirements, because with increase in rotor speed the power requirements increase rapidly and it is not satisfactory to operate at low speed because of a low value of heat-transfer coefficient. Also since volume holdup was found to be virtually independent of radius, whilst power requirements varied as radius cubed, it was concluded that a minimum radius and a maximum height should be employed with columns of this type.

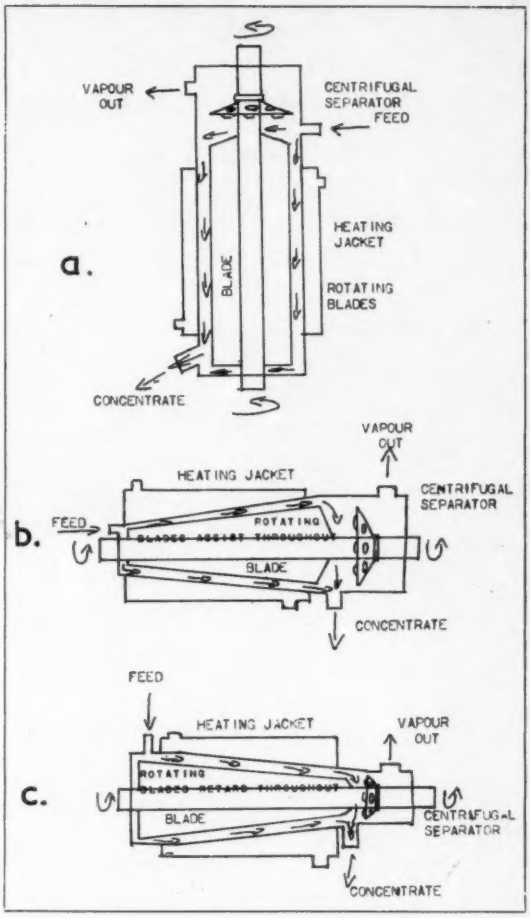

Fig. 3. Three types of agitated thin film evaporators[15]*: (a) vertical, straight-sided unit; (b) horizontal reverse-taper unit; (c) forward-taper unit*

Recently, Jones[24] has discussed the advantages of these agitated, thin-layer evaporators over the more conventional types. One particular merit reported by Jones was the ability to concentrate to a very viscous fluid in one pass. Concentrations of 8 : 1 or more were quite possible with these evaporators, whereas the normal falling-film evaporator would only give concentrations of about 2 : 1. Jones did not publish a complete correlation of his results, but the relationship between viscosity, temperature difference, throughput, etc., for both fixed and hinged-blade rotors were discussed and the results presented graphically.

A rather serious fault with rotary evaporators for certain duties was recently reported by Zacharius and Krudick.[25] This concerned the contamination of certain amino acid and other concentrates with copper and nickel, which appeared to have come from the rotary seal. However, Zacharius and Krudick reported the design of a short glass trap which, when inserted between the evaporator and the concentrate flask, appeared to cure this problem.

Other developments

The use of submerged combustion in evaporators was discussed by Cronan[18] in 1956, and particular mention was made of the use of this technique for the concentration of whey—a heat-sensitive material. The use of hot combustion gases for the evaporation of heat-sensitive material by direct contact was the subject of a recent patent.[19] A sketch to illustrate the principle of this design is shown in Fig. 6. There was an inner chamber (*A*) full of non-charrable, condensible fluid (usually water), which was positioned below the level of the liquid in the evaporator shell (*B*). The hot combustion gases passed into this inner chamber and bubbled through the water. During their passage through the water the gases cooled and some of the water was evaporated. The mixture of gas and vapour was

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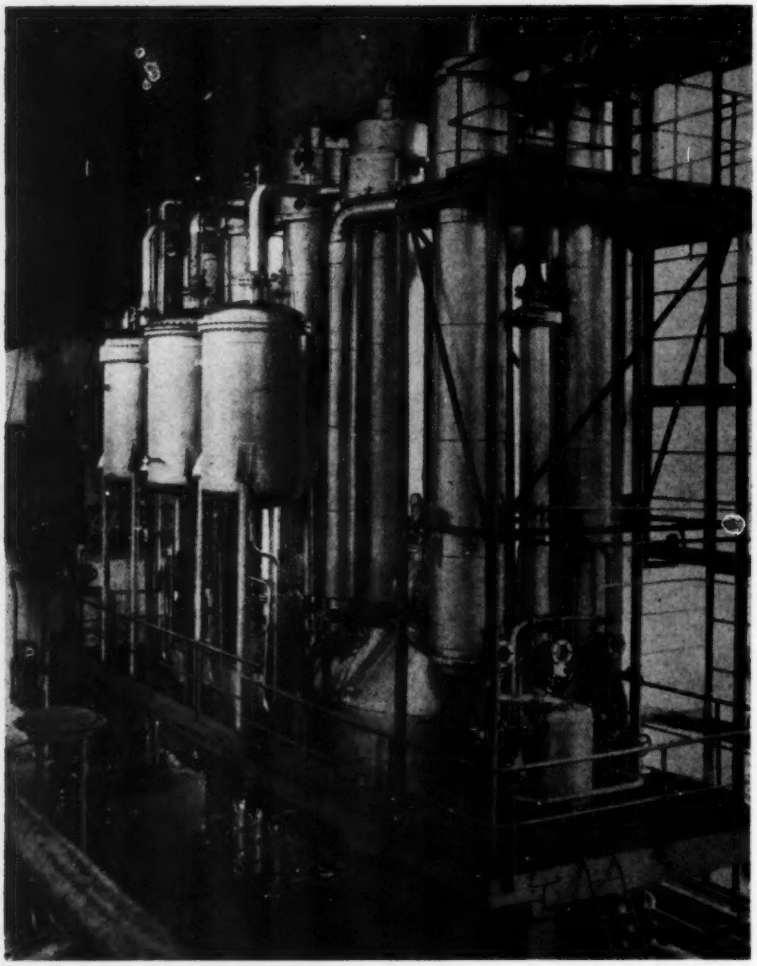

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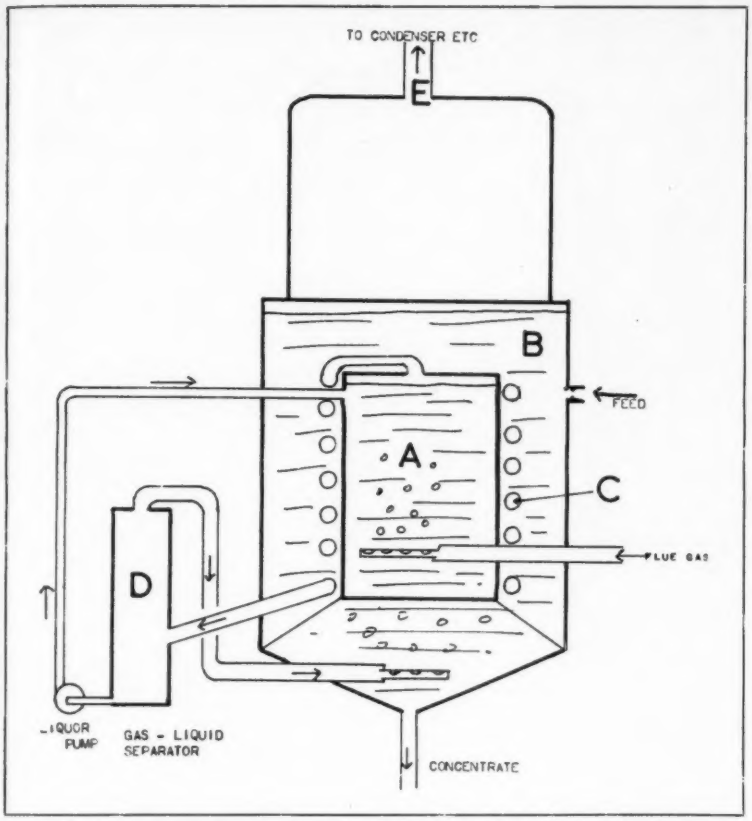

Fig. 6. An evaporator using direct flue gas heating for heat-sensitive materials[19]

then passed through a coil (*C*) also submerged below the surface of the heat-sensitive material. In this coil most of the water vapour condensed, the latent heat of condensation being passed through the tube wall into the liquid. The non-condensed gas was separated from the water in a gas-liquid separator (*D*), the liquid water being pumped back into the inner chamber. All or part of the now cooled gas was passed into the shell of the evaporator and its remaining heat was given up to the heat-sensitive liquid by direct contact. The usual condensing equipment, etc., was attached to the outlet (*E*) of the evaporator shell.

A further type of evaporator for heat-sensitive materials has recently been described.[20] A sketch is shown in Fig. 7. The design utilised a circulating stream of inert gas. Liquid was pumped into this stream at point *A*. The mixture was heated and a portion of the liquid evaporated in order to partially saturate the gas. The non-evaporated liquid was separated at *B* and the vapour-gas mixture cooled by heat exchange with the liquid-gas stream and finally cooled and separated at *C*. The inert gas, which was virtually free of vapour, was recirculated by a pump. Provision can be made for this design to operate in two or more effects.

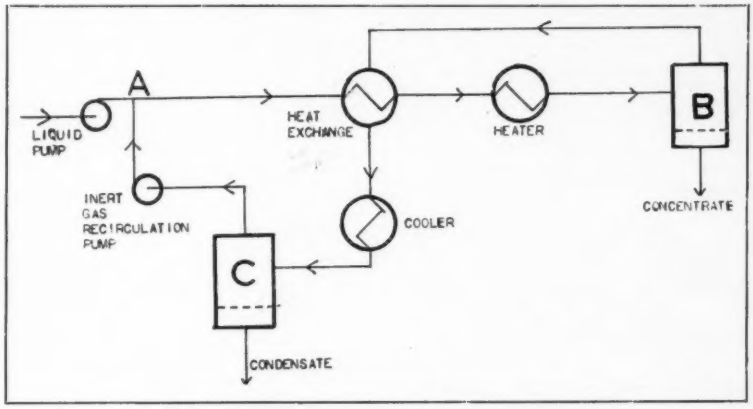

Fig. 7. An evaporator using a recirculating inert gas stream[20]

Selection of equipment

Many types of evaporator are commercially available and the choice of the optimum for any particular case is difficult. The solution to this problem lies in the integration of solution characteristics, evaporator-type characteristics and the economics of capital equipment and operating costs. A few of the variables which have to be considered are the physical properties of the solution to be evaporated, maintenance costs, labour costs, cooling water costs and equipment characteristics such as holdup, throughput, residence time, etc.

An examination of some of these variables together with suggested solutions for a few illustrative cases was made by Coston and Lindsey[21] in 1956. A few of the suggestions may be summarised.

Liquid viscosity

Up to 100 *cp.* A long-tube vertical or a calandria-type, forced circulation may be useful.

From 6 *to* 100 *cp.* Forced circulation, agitated thin film or falling film.

Above 100 *cp.* Drying equipment must be used or slow evaporation from an agitated film evaporator.

Heat-sensitive materials. Low temperature (high vacuum). Use forced-circulation or falling-film types. The agitated thin film is particularly useful because of the short time at temperature characteristics.

An example quoted by Coston and Lindsey for the concentration of orange juice suggested the use of either a falling film with recirculation of the liquor or an agitated film evaporator.

Design calculations

Coates and Pressburg[22] have recently published a simplified method for the solution of multi-effect evaporator problems. This method, which is less time-consuming than the established design methods, is claimed to

check on the average to within 2% of the more exact calculation and a maximum error of 7% is reported.

The tediousness of conventional design calculations was also discussed by Wise,[26] and a graphical design method was proposed. This method was based on the concept of 'overall thermal resistances' rather than 'overall heat-transfer coefficients'. Wise claimed that this graphical approach led to a considerable simplification in the presentation of multiple-effect problems.

Cost factors

The importance of physical design, flow sheet and heat reclamation in the design and costing of evaporators was illustrated by Kohlins and Englander[23] in 1956. An attempt was made to show how savings could be effected.

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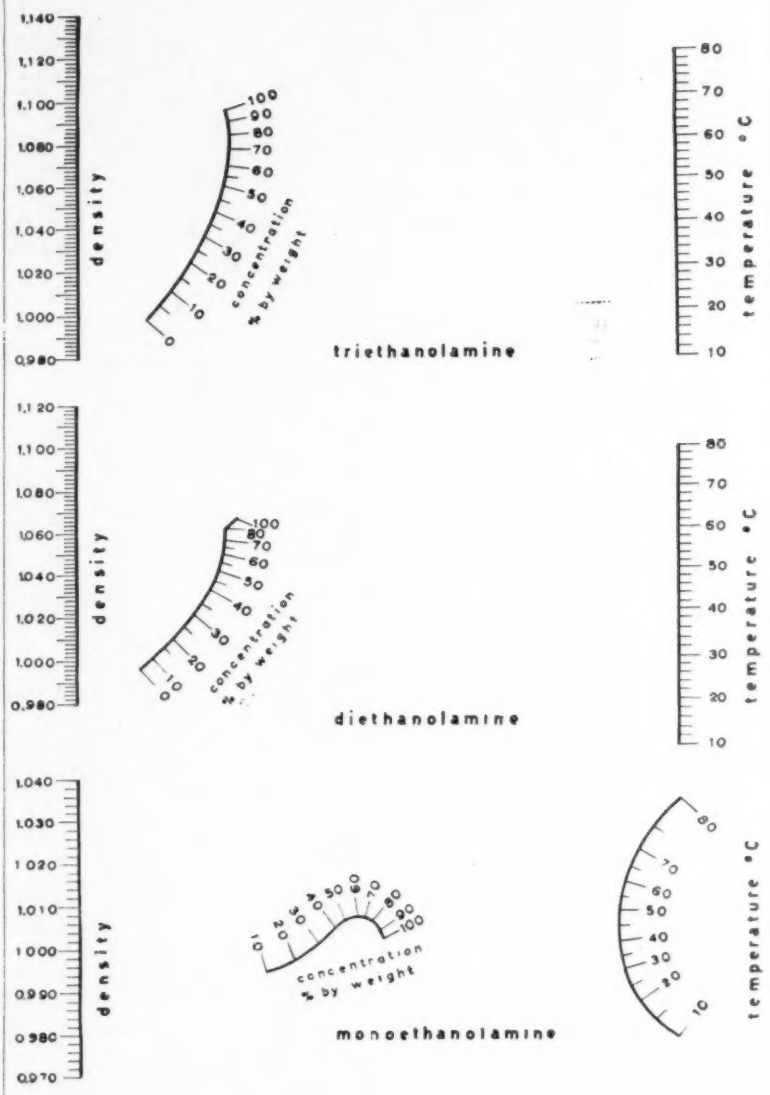
Densities of Aqueous Solutions of the Ethanolamines

By A. M. P. Tans*



The accompanying nomographs give the densities of aqueous solutions of mono-, di- and triethanolamine respectively.

The nomographs have been constructed from the measurements of Leibush and Shorina.[1]

The mean deviation of the values read off from the nomographs, as compared with the measured values, amounts to ± 0.001 for the three ethanolamines. The maximum deviation amounts to –0.003 for monoethanolamine at 20% and 30° to 50°C., and likewise –0.003 for triethanolamine at 100% and 10° to 30°C.

For zero concentration (pure water) the nomographs only hold up to 50°C.

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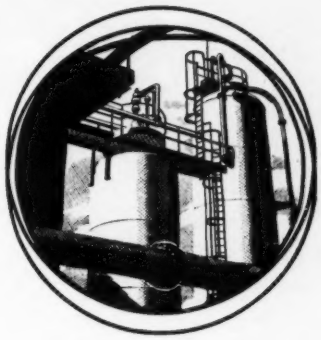
[1]A. G. Leibush and E. D. Shorina, *Zhur. Prikl. Khim.*, 1947, **20**, 69/76.

**Central Laboratory, Staatsmijnen, Geleen, Netherlands.*

Materials of Construction for Chemical Plant



TITANIUM

By B. J. Connolly,* B.Sc., A.I.M.
and R. J. Watkins,* B.Sc., A.C.T.(Birm.)

This is the ninth article in our series 'Materials of Construction for Chemical Plant', which has included PVC, lead, nickel, stainless steel, graphite, polyolefines, copper and timber. Although titanium is a relative newcomer, it has already established itself as a permanent addition to the range of materials available to the chemical engineer, and has been adopted for a diversity of chemical plant on an increasing scale of size and usage.

As a result of the interest of the aircraft industry in high strength/weight ratio, titanium and its alloys first became commercially available in the U.S. in 1950 and in the U.K. by 1952. Initially only relatively small quantities were produced, largely for evaluation, but by the end of 1954 demand had grown to such an extent that, for example, a 1,500-ton-p.a. melting plant was commissioned in the U.K. By this time laboratory work had indicated that titanium possessed such outstanding corrosion resistance towards many aggressive media that it merited serious consideration as a material of construction for chemical plant. Furthermore, the newly installed capacity provided for the first time sufficient metal to satisfy current aircraft needs and to release material for fabrication into chemical plant.

Manufacture and availability

In the U.K., titanium granules, the raw material from which titanium ingots are cast, are made by the sodium reduction process, as compared with the sponge produced by the magnesium reduction process generally used elsewhere. The ore, rutile (TiO_2), is chlorinated at between 700° and 1,000°C. in the presence of carbon to produce titanium tetrachloride, which is condensed, purified by distillation, and then reduced by carefully cleaned sodium at high temperature under a protective dry argon atmosphere. The resulting titanium metal granules are leached with water to remove sodium chloride.

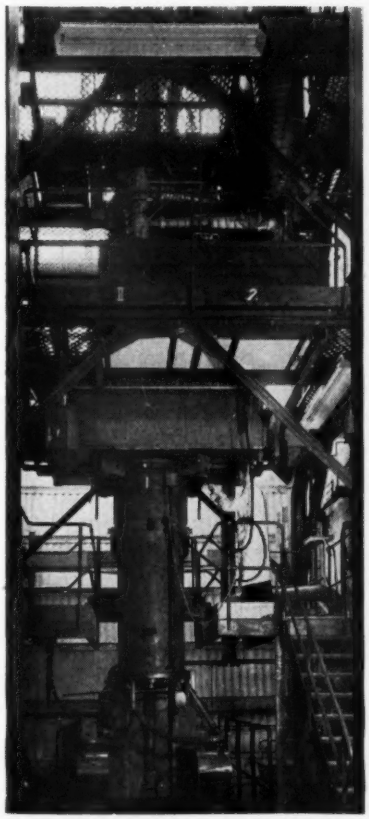


Fig. 1. Fully assembled vacuum electric arc furnace for melting titanium ingots up to 4,200 lb.

Large electrodes made by compacting the granules are consumably arc melted in a vacuum furnace of the type illustrated in Fig. 1 and, to ensure complete melting and homogeneity, the resulting ingot is remelted in the same furnace. Water-cooled copper crucibles are employed to prevent contamination of the melt which would otherwise occur if conventional refractory linings were used.

Ingots weighing up to 2 tons are now being produced as the starting point from which the complete range of wrought forms is made. These comprise bar, rod, wire, plate, sheet, strip, tube and simple extrusions. A comprehensive survey of the production of wrought titanium has been presented by Crane.[1]

Mechanical and physical properties

Typical mechanical properties of annealed commercially pure grades of titanium and of titanium alloys are listed in Tables 1 and 2 respectively. In general the commercially pure material is used for chemical applications and the choice of grade, from the very soft titanium 115 to the

*Metals Division, Imperial Chemical Industries Ltd.

Table 1. Mechanical properties—commercially pure titanium

	I.C.I. Titanium 115	*I.C.I. Titanium* 120	*I.C.I. Titanium* 125	*I.C.I. Titanium* 130	*I.C.I. Titanium* 150	*I.C.I. Titanium* 160
Tensile strength (tons/sq.in.)	26 max.	30 max.	25–35	30–40	35–45	40–50
0.1% proof stress (min.) (tons/sq.in.)	13	15	18	22*	25	30
Elongation (min.) (% on 2 in.)	30	25	22	20	18	15†
Young's modulus (typical) (10^6 lb./sq.in.) ..	15–17	15–17	15–17	15–17	15–17	15–18
Fatigue limit (approx.) (% of tensile strength) ..	50	50	50	50	50	50
Bend radius (on 16 s.w.g.)	1T	1T	1T	1T	1T	2T
Density (g./cu.cm.)	4.51	4.51	4.51	4.51	4.51	4.51

* 20 min. on rod. † 18% on $\sqrt[4]{}$A.

Table 2. Mechanical properties—titanium alloys

	I.C.I. Titanium 314C	*I.C.I. Titanium* 314A	*I.C.I. Titanium* 317	*I.C.I. Titanium* 318A	*I.C.I. Titanium* 230		*I.C.I. Titanium* 679	
					Solution treated	*Aged*	*At 20°C.*	*At 500°C.*
Tensile strength (tons/sq.in.)	42–52	62 min.	52* min.	62 min.	32–45	45–53 typical	67 min.	52 typical
0.1% proof stress (tons/sq.in.)	30 min.	57 min.	45 min.	57 min.	25–37	37–45 typical	58 min.	38 typical
Elongation (% on $\sqrt[4]{}$A)	20 min.	15 min.	12 min.	10† min.	20 min.	20–24 typical	12 min.	19 typical
Young's modulus (typical) (10^6 lb./sq.in.)	15–18	16–19	15–18	15–17	15–17	15–17	14–17	—
Fatigue limit (approx.) (% of tensile strength)	60–65	60–65	50	60–65	—	—	58	—
Bend radius (on 16 s.w.g.)	—	—	4T max.	4T max.	2T max.	—	—	—
Stress for 0.1% total plastic strain in 300 hr. (tons/sq.in.)	—	—	—	—	—	—	At 400°C. 36 approx.	12½ approx.
Density (g./cu.cm.)	4.51	4.51	4.46	4.42	4.56	4.56	4.84	4.84

* 50 min. on sheet. † 8% on 2 in. Unless otherwise stated, all properties refer to the annealed condition.

Table 3. Comparative physical properties of titanium

Atomic number: 22		Atomic weight: 47.9					
Crystal structure Below 882°C. Close-packed hexagonal (alpha) a = 2.9504 Å c = 4.683 Å c/a = 1.587		Above 882°C. Body-centred cubic (beta) a = 3.3065 Å (900°C.)					
	Titanium	*Cu*	*Fe*	18/8/*Ti* stainless steel	'*Monel*'	'*Hastelloy*' *C*
Melting point (°C.)	1,660 ± 10	1,084	1,535	1,500 approx.	1,300/1,350	1,270/1,305
Density (g./cu.cm.)	4.51	8.94	7.86	7.90	8.83	8.94
Thermal conductivity (cal./cm./sq.cm./°C./sec. at 20°C.)	0.0407	0.92	0.17	0.038	0.062	0.03
Electrical resistivity (microhm-cm. at 20°C.)	48.2	1.72	10.0	73.0	48.0	133.0
Specific heat (cal./g./°C. at 50°C.)	0.126	0.093	0.109	0.12	0.127	0.092
Coefficient of thermal expansion (10^{-6}/°C. : 0–100°C.)	8.9	16.4	11.9	16.0	14.0	11.3
Elastic modulus (10^6 lb./sq.in.)	15.0	17.5	29.0	29.0	23/26	24.5

[Courtesy of Hathernware Ltd.

Fig. 2. Titanium pump impeller for handling sodium hypochlorite liquor

hardest, titanium 160, depends upon the end use. It will be seen from the tables that materials offering a wide range of tensile strength are available, comparable with those obtainable from carbon steel up to those of highly alloyed steels. It should be noted, however, that the elastic modulus of titanium is only about half that of steel.

The physical properties of titanium, compared with those of certain other metals and alloys, are reproduced in Table 3. A particular point to note is that the coefficients of thermal expansion of iron and titanium are sufficiently close to enable mild-steel vessels lined with titanium to be operated at moderately elevated temperatures and pressures without detriment to the lining. Also, from the point of view of heat-exchange performance, although the thermal conductivity of titanium is close to that of austenitic stainless steel, the fact that thin-walled titanium is used and only a low fouling factor is employed in design calculations, the overall heat-transfer characteristic of titanium units is quite high.

Corrosion resistance

The corrosion behaviour of titanium has been evaluated for a wide range of pure corrodents in the laboratory, as well as in many aggressive mixtures constituting plant liquors, by exposing specimens in the actual plants. One of the more recent comprehensive surveys of corrosion data for titanium is that of Barber,[2] which tabulates results of numerous tests under both sets of conditions. These trials have demonstrated that titanium possesses outstanding resistance towards such media as sea-water, brines and most other metal chlorides, sodium chlorite, chlorate and hypochlorite solutions, wet chlorine and chlorine dioxide. It is also virtually unaffected by strong oxidants, such as chromic and perchloric acid and nitric acid of all strengths except red fuming acid, as well as many organic acids.

Because it depends for its corrosion resistance on the formation and maintenance of a thin oxide film, titanium is not generally suitable for use in moderate and high strengths of reducing acids, including sulphuric and hydrochloric acids, particularly at elevated temperatures. In certain instances, however, the presence of oxidising agents, for example chromic or nitric acids in sulphuric acid or free chlorine in hydrochloric acid, will markedly reduce the rate of attack to a tolerable level. Similarly the inhibiting effect of as little as 0.005 mol./l. of ferric or cupric ions in solutions of these acids has been reported.[3]

This has permitted the use of titanium, for example as a rotating pickling drum operating in hot sulphuric acid containing copper sulphate, and underlines the importance of plant trials in determining the effect of impurities in the liquors used. Cotton[4] has described a method of anodic polarisation of titanium equipment to increase the range of temperature and concentration of reducing acids in which the metal can be employed. The corrosion resistance of titanium alloys is generally similar to that of titanium itself.

Commercially pure titanium exhibits a high resistance to pitting attack, even under differential aeration conditions, to stress-corrosion cracking and to corrosion fatigue, being in these respects superior to stainless steel, particularly in chloride solutions. Thus, for example, the only reported stress-corrosion failure of the commercially pure metal has been in boiling red fuming nitric acid and in certain methanol solutions; higher alcohols do not appear to be deleterious.

Uses of titanium

Among the early applications of the metal was its use for nozzles, thermowells and a lining for a chlorine dioxide mixer on a paper pulp plant, and also for a tubular heat exchanger handling 15% sodium hypochlorite.[5] After five years' service these components are still free from corrosion.

The handling of chlorine-bearing liquors and wet chlorine-bearing gases is still one of the major uses of titanium in chemical plant. Its complete freedom from attack by boiling sodium chlorite solutions and chlorine dioxide vapours makes it a most desirable material for textile bleaching equipment using chlorite as the bleaching agent. In the last 12 months almost one ton of titanium has been ordered for the manufacture of four textile bleaching machines in the U.K., and there is every indication that titanium will become a constructional material of major importance in this field. Heat

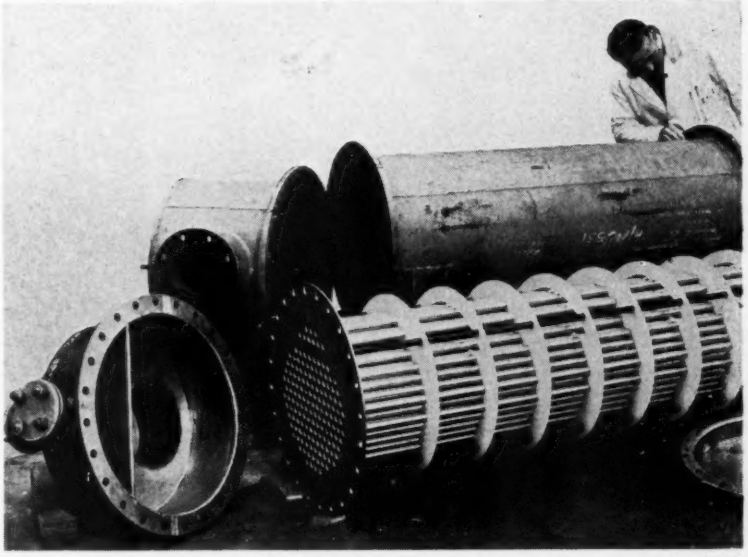


Fig. 3. Wet chlorine condenser in titanium containing 151 tubes. End covers are lined with 20 swg. titanium sheet

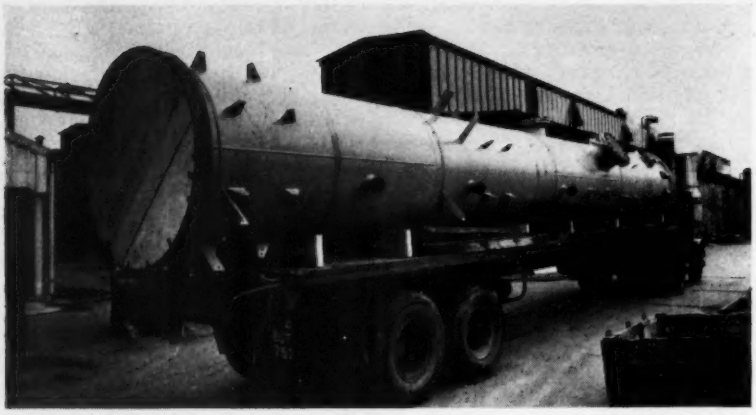


Fig. 4. Chemical plant distillation column about 40 ft. long × 5 ft. diam. Lined for some 30 ft. of its length with 16 s.w.g. titanium sheet and containing 20 titanium distillation trays

exchangers, lined vessels and pump impellers have been supplied for firms in Great Britain, Holland and Germany for handling sodium chlorate/chlorine dioxide mixtures, sodium hypochlorite and wet chlorine gas. Fig. 2 illustrates a typical titanium pump impeller which has given excellent service in a pump on caustic soda/sodium hypochlorite duty and Fig. 3 shows a tube-in-shell heat exchanger which is being used as a wet chlorine condenser.

Plate-type heat exchangers in titanium have been supplied to firms in England, Holland, Germany and South Africa for service in a variety of chlorinated liquors. Three units incorporating well over half a ton weight of titanium have given completely satisfactory service over a period of more than 12 months in this country. The excellent ductility of commercially pure titanium makes it especially suitable for the heat-exchanger plates which are quite complicated pressings.

Organic chemical synthesis

Titanium is being used in the synthesis of various organic chemicals and its attractiveness for this purpose lies not only in its resistance to corrosion, but also in its ability to suppress certain undesirable chemical side-reactions which occur with other materials of construction. One such plant incorporating 12 tons of I.C.I. titanium is in the course of construction at the present time. The largest vessel in the plant is a distillation column 40 ft. long × 5 ft. diam. (Fig. 4) which is lined with 16 s.w.g. titanium sheet and which contains 20 distillation trays. There are two large high-pressure stirred reactors each 5 ft. diam. × 11 ft. long, two large storage tanks 10 ft. diam. × 18 ft. long, several heat exchangers, including two condensers each with a ton of titanium tubing in them, pumps and a large quantity of piping up to 8 in. diam.

All this equipment is either lined with 16 s.w.g. titanium or is made from solid titanium, $\frac{3}{16}$ to $\frac{1}{4}$ in. thick. Fig. 5 shows the excellent quality of the tube-to-tube plate welds which is attainable by automatic argon-arc techniques in heat-exchanger fabrication.

Nitric acid concentration

Another major potential application for titanium is in the manufacture of concentrated nitric acid (99.5 to 99.8%) for making explosives. Because of the strongly oxidising nature of the acid, titanium is particularly suited to this duty and recent research within I.C.I. has shown that, as long as the NO_2 content of the 99.8% acid is less than 1%, there is no danger of a pyrophoric reaction between titanium and the acid. In fact, the permissible NO_2 content is believed to be considerably above 1% and possibly in excess of 10%.

Considerable use is being made of the ability of titanium to withstand these conditions and in a new concentrated nitric acid plant being built in Scotland the metal is being used for pumps, coolers, piping, level and flow control instruments, etc. Fig. 6 illustrates one of four titanium submerged pumps, and its component parts, which are being installed on this plant. Each pump contains 100 lb. weight of titanium and one of them already installed has given an excellent performance in service.

Nuclear fuel processing

In the chemical processing of irradiated nuclear fuel elements, boiling strong nitric acid solutions are used, and titanium has been shown fully to resist these conditions. The solutions involved are highly radioactive and the equipment which contains them must have an almost indefinite life. Titanium has been thoroughly tested in the laboratory and on the plant and the U.K.A.E.A. have recently taken delivery of a prototype titanium evaporator. Several other evaporators and a large dissolver vessel are now being designed for nuclear chemical processing plant.

Anodising jigs and racks

Titanium has become an established material of construction for jigs and racks in the anodising industry and in Great Britain alone over 150 firms are

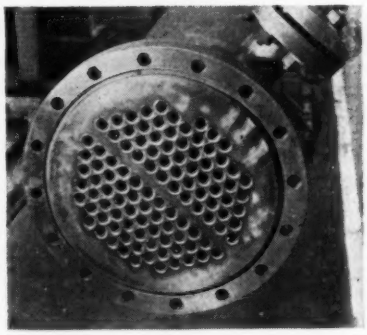


Fig. 5. Showing the excellent tube-to-tube plate weld quality achievable with titanium. This heat exchanger is one of two recently supplied to Elektrochemische Werke Munchen A.G., Western Germany

now using it for this purpose. Hoover (Washing Machines) Ltd. have successfully used titanium jigs on a production line[6] and they now have more than 60 solid titanium jigs and more than 400 titanium-tipped aluminium jigs in service. Owing to the build-up of protective anodic film when the current is switched on, titanium is rendered completely passive in anodising solutions. This film possesses the remarkable property of becoming electrically conductive when the workpiece is brought into contact with it, so that the flow of current is unimpeded whilst the titanium jig is continuously protected from corrosion.

Costly jig maintenance is eliminated because titanium has an indefinite life in these conditions, and the stripping operation necessary with aluminium jigs, because of the build-up of the non-conductive oxide film, is also

eliminated, thus reducing production costs. A typical titanium anodising jig is illustrated in Fig. 7.

Heating coils for plating

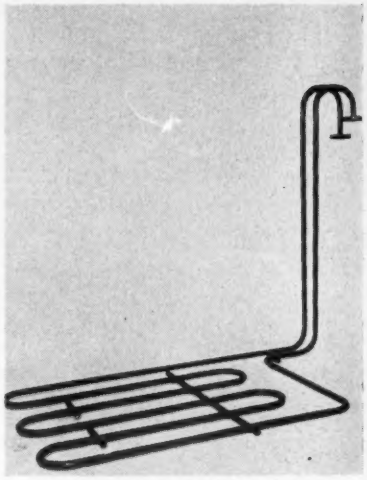
Titanium is rapidly becoming a standard material for heating and cooling coils used in the electroplating industry where its resistance to most chromium, nickel and copper plating solutions has been shown to be excellent. It is completely inert in boiling chromic acid/sulphuric acid liquors, and a set of coils was found to be in perfect condition after more than one year's service under these conditions.[7]

On the basis of corrosion resistance a life of at least 15 years can be expected from thin-walled titanium tubing, which is much lighter and more convenient to handle than lead tubing which has been used in the past. However, in fluoride-bearing solutions the life of titanium is limited to one to two years. By standardising on the design and the size of tubing from which they are made, the cost of titanium heating coils has been brought down to a level which makes them directly competitive with earlier materials of construction. Fig. 8 illustrates a typical titanium heating coil. For very large installations, internal coils may be insufficient for heating or cooling purposes and external heat exchangers in titanium can be used in their place. Titanium is also being used for anode hooks and submerged anode busbars in electroplating baths. The electrical conductivity of busbars can be increased by employing a copper-cored titanium conductor, which has the conductivity of pure copper, with the corrosion resistance provided by the outer titanium sheath.

Compressor valve plates and springs

The corrosion resistance of titanium and its alloys makes them especially suitable for reciprocating components which are subject to failure by corrosion fatigue, *e.g.* in wet, sulphur-bearing gases such as hydrogen sulphide. Furthermore, the high strength/weight ratio is an advantage and titanium alloys are being used to an increasing extent for the valve plates and springs in ordinary air compressors as well as gas compressors.

Titanium alloy valve plates have now completed well over 20,000 hours' service in an ammonia synthesis compressor handling nitrogen and hydrogen at pressures up to 55 atm., which is more than three times the average life obtained with steel valve plates, and titanium alloy springs have given lives in excess of 22,000 hr. in the same conditions compared with about 300 hr. for stainless-steel springs.

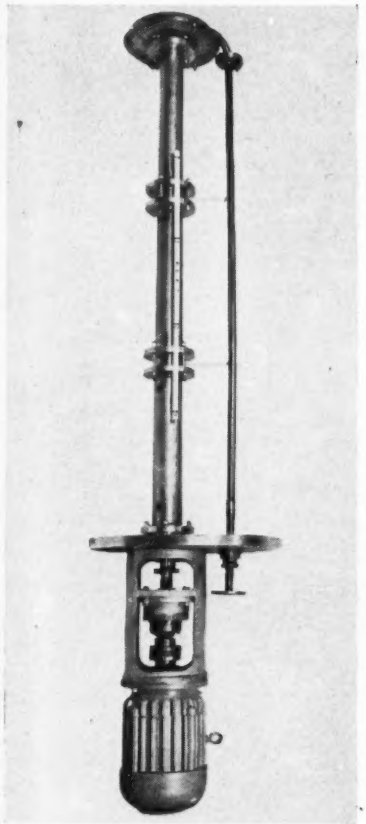


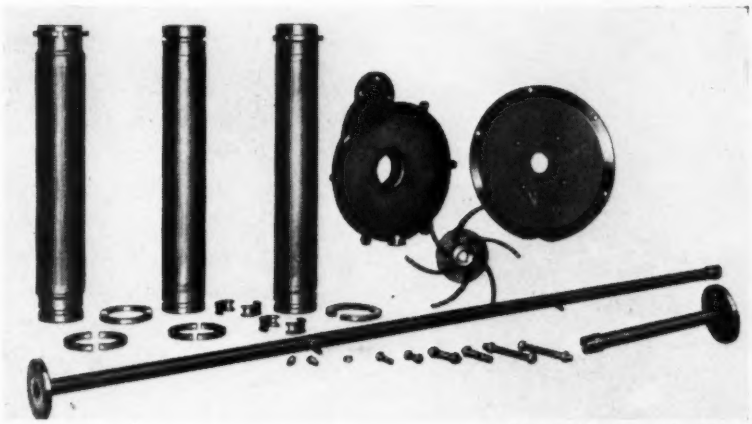
[Courtesy of Electrochemical Engineering Co. Ltd.

Fig. 8. Fabricated titanium heating coil supplied to Jaguar Cars Ltd. for a new chromium plating plant

In plain air compressors, titanium is also finding considerable use and one well-known air compressor manufacturer in England has designed a new type of portable high-speed unit, utilising the properties of titanium. This machine has a larger valve lift than normal which has been made possible by the use of titanium. Another very large compressor firm has done exhaustive tests with titanium in a machine in which the valve lift was intentionally increased to make the conditions more severe, and titanium has so far outlasted steel by more than three times under these conditions.

At present, titanium valve plates are usually made in an alloy having





[Courtesy of Appleton and Howard Ltd.

Fig. 6. Appleton & Howard Gush Type 'S' submerged centrifugal chemical pump (1½ in. suction). Fabricated ⅜ in. thick titanium back plate and casing. Fabricated 10 in. maximum diameter titanium impeller. Fabricated solid ⅛ in. and ⅝ in. titanium centre tubes and 1 in. bore × 20 s.w.g. titanium lift pipe

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Corrosion was a hardy annual until he consulted ICI Metals Division. But they suggested that an application of titanium would go to the root of his problem.

With its outstanding resistance to corrosion, titanium provides the answer to many problems posed by aggressive service conditions. In chemical plant, ICI Titanium is being used for lining reaction vessels and other large-scale equipment; for complete components ranging in size and complexity from compressor valve plates to large heat exchangers; for economic, trouble-free anodising jigs; for non-consumable anodes; and for virtually indestructible heating coils.

ICI Metals Division probably have wider knowledge of titanium and its applications than anyone else in Europe. They can often suggest a fresh line of approach to corrosion problems in chemical plant. See if they can help you.

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TITANIUM

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a tensile strength in the region of 55 to 60 tons/sq.in., whilst springs are made of hard-drawn alloy wire with a tensile range of 85 to 90 tons/sq.in. Even at this high strength level the titanium alloy wire has sufficient ductility to enable the springs to be cold coiled.

Cost of titanium equipment

Assuming a $\frac{3}{8}$-in.-thick mild-steel vessel with a 20 s.w.g. (0.036 in.) titanium sheet lining, the price for the complete vessel, including all material and fabrication, is only just over twice that of a $\frac{3}{8}$-in.-thick vessel of similar dimensions and made wholly in stainless steel. This extra cost is usually quickly recovered by reduced maintenance charges and increased plant availability. The price for a titanium lining varies from approximately £8/sq.ft. for a simple vessel to about £10 to £13/sq.ft. for more complicated vessels with branch pipes and dished ends, etc.

Design and future trends

Because of the high price of titanium relative to other materials of construction, it is necessary to employ thin sheet linings, generally of the order of 20 s.w.g. (0.036 in.) inside mild-steel vessels, and well-proven fabricating techniques are available for applying such linings to complicated as well as simple vessels, the size of vessel which can be lined being virtually unlimited. However, some chemical plant vessels have already been fabricated in thick titanium ($\frac{3}{16}$ to $\frac{3}{8}$ in.) and the tendency for this construction to be used will increase in the future as the price of titanium is reduced.

Titanium heat exchangers are being used to an increasing extent, both tubular and plate-type units having already given excellent service. As explained above, the thermal conductivity of titanium is low, but, because of its high resistance to corrosion, thin-walled material is used which affords improved overall heat-transfer characteristics as compared with less-resistant materials. In the case of plate heat exchangers the freedom from fouling by corrosion products is a big advantage in favour of titanium. There is every indication that titanium heat-exchange units will be used more and more in the future, particularly for handling wet chlorine compounds, concentrated nitric acid and the like.

In the design of chemical plant vessels incorporating titanium it is necessary to choose the correct grade of the metal to suit the particular component and conditions. For simple vessels the lining is usually made in commercially pure I.C.I. titanium 130, the softer 120 and 115 grades being used for progressively more complicated vessels, particularly where there are a number of welds crossing each other.

For tubular heat exchangers, titanium 125 and 130 are used for tubes and tube plates respectively, but in the case of plate-type units the softest grade, titanium 115, is used, since maximum ductility is required in the pressing of the plates. On the other hand, the harder grades of titanium are used for the manufacture of compressor valve plates where maximum strength/weight ratio is required and an alloy of titanium, titanium 317, has been used with considerable success. Field tests have, however, shown that the hard grade of the commercially pure metal, titanium 160, may well have adequate strength for valve plates and there is a considerable price advantage to be gained in using this latter grade.

Price is still the main deterrent towards using large quantities of titanium for applications where conventional materials have a reasonable life, and its use has so far been largely confined to those cases where there is a compelling technical advantage to be gained in using it. However, the price is being steadily reduced and is now less than half what it was four years ago. With further price reductions to follow in the future, and on the basis of data already established which points to great advantages as a material of construction in this field, the uptake of titanium and its alloys by industry will be seen to increase progressively.

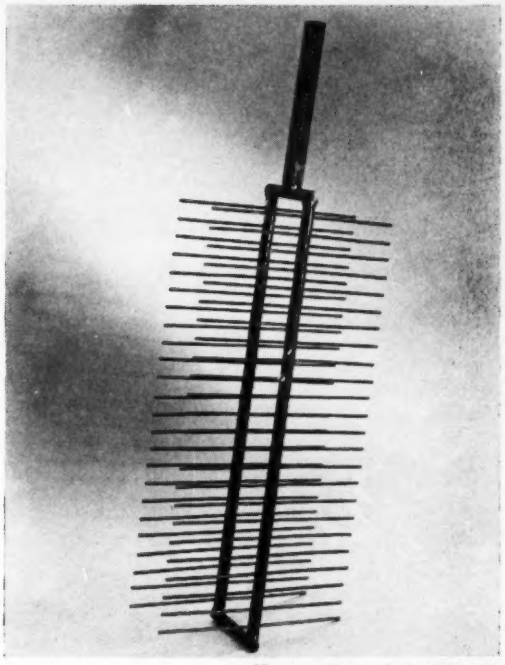

Fig. 7. All-titanium anodising jig

[Courtesy of Haynes, Ford and Elliot Ltd.

The material of construction for chemical plant which will be discussed in next month's issue of CHEMICAL & PROCESS ENGINEERING will be

ALUMINIUM

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[4] J. B. Cotton, *Chem. & Ind.*, 1958, 68-69.
[5] H. B. Bomberger, *Ind. Eng. Chem.*, 1957, **49**, 1658.
[6] *Product Finishing*, December 1959.
[7] *Steel*, 1958, **143**, 62.

Personal Paragraphs

★ **Mr. C. S. Garland,** a former vice-president of the Society of Chemical Industry and a president of the National Union of Manufacturers, died recently aged 73. Mr. Garland was a chemist and chemical engineer and was well known for the commercial application of the streamline principle of filtration. He had many interests in education and was a director of several companies in the electrical and chemical engineering industries. He was an M.P. in 1922. Mr. W. Leonard Hill, publisher of CHEMICAL AND PROCESS ENGINEERING, writes, 'I recall with great pleasure Mr. Garland's kindness on several occasions, particularly when, with Prof. J. W. Hinchley, he gave me valuable advice on the establishment of "The Chemical Engineering and Chemical Catalogue", now the "Chemical Engineering Data Book"'.

Mr. R. W. Ricketts

Sir Alexander Fleck

★ **Mr. R. W. Ricketts** has joined Reddish Chemical Co. Ltd. as an executive on the brewing and mineral-water side of their activities. He has spent four years with the Brewing Industry Research Foundation, where he has been participating in the discovery and development of nylon treatment for the stabilising of bottled beers.

★ **Sir Alexander Fleck,** F.R.S., was made a Baron in the New Year Honours list, for public services. He is chairman of the Advisory Council on Research and Development of the Ministry of Power and of the Nuclear Safety Advisory Committee. He was chairman of I.C.I. Ltd. from 1953-60.

★ **Mr. Alfred Ratcliffe** has been appointed a director of metals division of I.C.I. Ltd. and a joint managing delegate director of Marston Excelsior Ltd., a subsidiary company. For the last nine years he has been production director and latterly also engineering director of I.C.I. salt division.

★ **The Rt. Hon. Viscount Amory of Tiverton,** P.C., has been appointed a non-executive director of I.C.I. Ltd.

★ **Mr. G. E. Beharrell,** chairman of the Dunlop Rubber Co. Ltd., is one of the Knights Bachelor in the New Year Honours List. He has been with the company since 1928; in 1945 he was made managing director and in 1957 chairman of the group. He has been president of the Federation of British Rubber and Allied Manufacturers' Association and is at present also chairman of the International Synthetic Rubber Co. Ltd.

Mr. Norman Daniel

Mr. G. E. Beharrell

★ **Mr. Norman Daniel,** assistant general manager of Semtex Ltd., has been appointed general purchasing manager for the parent group—Dunlop Group.

★ **Mr. Clifford Passmore** has been appointed field regional sales manager for the Midland region of Griffin & George Group of companies. He has been with the group for 10 years.

★ Five new directors have been appointed to the board of John B. Pillin Ltd., a member of the Castrol Group. They are **Messrs. R. Adams, J. A. P. Coe, L. J. Field, A. F. MacDonald** and **J. W. MacMahon.**

COMICAL ENGINEERING CORNER

"THERE GOES THREE YEARS SMOKELESS FUEL RESEARCH"

★ **Dr. A. Trevor Churchman** has been appointed deputy director of the Central Electricity Generating Board's Berkeley Nuclear Laboratories. He joined the board as head of the materials division of the new laboratories at Berkeley in 1959 which appointment he retains in addition to his new one.

Mr. Robert M. Atkinson

Mr. J. Arthur Reavell

★ **Mr. J. Arthur Reavell,** chairman of the Kestner Evaporator & Engineering Co. Ltd. and the Kestner Group of companies, retired from the chair at the end of last year after 53 years with the company and assumed the appointment as the company's first president. He founded the company in 1908. He was a founder member of the Institution of Chemical Engineers and was president in 1929-30.

★ The death occurred recently of **Mr. Robert M. Atkinson,** chairman of Sulzer Bros. (London) Ltd. He spent some 30 years in the Vickers organisation before he joined Sulzer Bros. (London) Ltd. in 1938 as managing director.

★ **Mr. L. Coltman,** formerly of Insulators Ltd. has been appointed to the board of directors of Moto Plastics Ltd. With more than 18 years' experience in plastics, more recently in reinforced plastics, he will be engaged in sales promotion in this field.

★ **Mr. E. B. Thompson,** sales manager of Ekco Electronics Ltd., has been elected chairman of the nucleonics group of the Scientific Instrument Manufacturers' Association.

★ **Dr. M. Josephs** has been appointed to the newly created post of market research manager of Price's (Bromborough) Ltd. He will be responsible for investigating new directions in which the company's experience in chemicals derived from oils and fats can be of value. He was till recently, research and development manager of John Knight Ltd.

What's New

in Plant • Equipment • Materials • Processes

CPE reference numbers are appended to all items appearing in these pages to make it easy for readers to obtain quickly, and free of charge, full details of any equipment, machinery, materials, processes, etc., in which they are interested. Simply fill in the top postcard attached, giving the appropriate reference number(s), and post it.

Cleaning heat exchangers

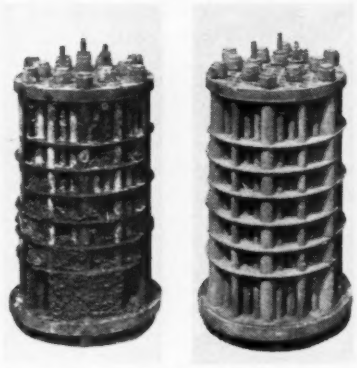
Processes for the removal of grease and dirt, as well as scale on the water side, from all types of heat exchanger are offered by Atlas Preservative Co. Ltd.

In the vapour process a portable vaporiser is coupled to the lowest point of the heat exchanger. The application of heat in the form of steam or electricity to the vaporiser causes the degreasing solvent to vaporise, rise into the heat exchanger, condense on the tubes where it dissolves the grease, etc., and run back into the vaporiser. Subsequently it re-vaporises, leaving the grease, which has a higher boiling point, behind.

The *Atlas Greeskilla* when dissolved in hot water and circulated can be used to remove grease and dirt from pipe systems, heat exchangers and machinery generally. The solution is made in varying strengths as outlined in the maker's instructions, depending on the type of plant and grease to be removed.

Scale from the water side of heat exchangers can be removed by circulating *Atlas Condenflu* through the tubes. This is an inhibited acid which is said to be dissolve scale deposits without having any detrimental effect on the metals used in the construction of the unit, nor does it affect rubber, composition packings and wood. It is diluted with water and circulated round the unit to be cleaned.

CPE 1622



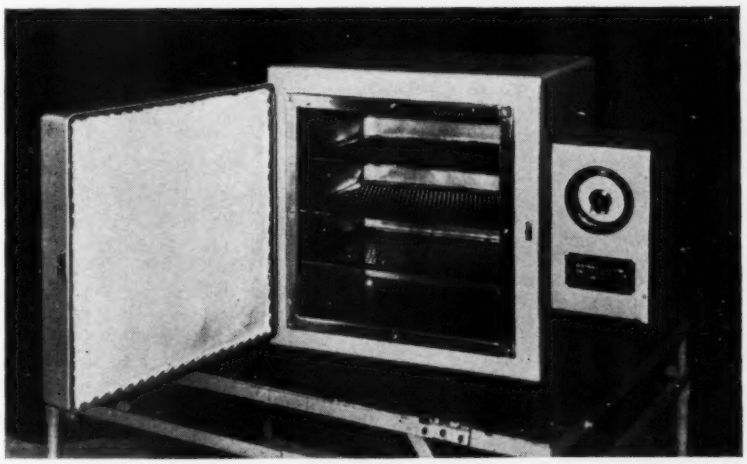
A heat exchanger before and after treatment with 'Greeskilla'

Laboratory-size oven

Isopad Ltd. offer an oven designed to meet the special requirements for a high-temperature laboratory-size oven. The inner stainless-steel casing is backed by 3 in. of thermal lagging, and the outer casing is stove-enamelled mild steel.

Three stainless-steel trays are fitted and the oven temperature is automatically controlled by a mercury-in-steel contact thermometer calibrated 0° to 800°C. A loading of 1,800 W is sufficient for the operating temperature of up to 500°C.

Ovens of this nature are also made in larger dimensions as well as in the special design suitable for use in flameproof areas Group II and III; in that case, the heating elements are metal sheathed and mineral insulated. They terminate in flameproof glands and flameproof terminal boxes. The element temperature must, of course, be kept below the spontaneous ignition temperature of explosive gases or liquids present, for which purpose a range of controls in flameproof housings or automatic intrinsically safe controls are available. **CPE 1623**



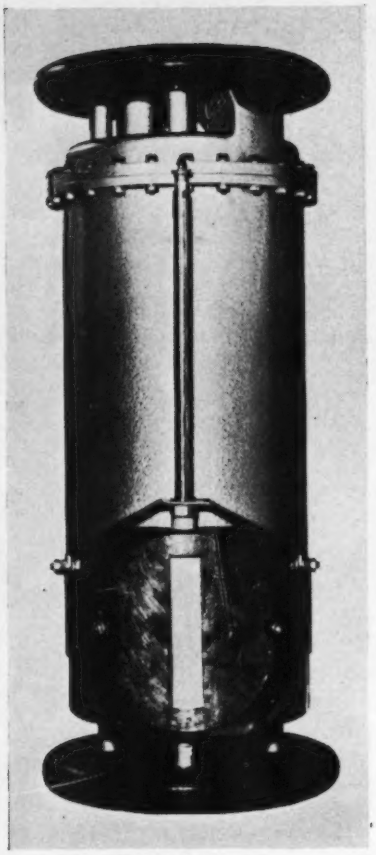
Laboratory oven

X-ray unit

A new portable X-ray unit of 150-kV capacity and a weight of 51½ lb. is offered by Pantak Ltd. It is available in two models, one having a 60° field and the other a 360° field.

A particular feature of the offset head is its use, especially in the panoramic version, in the examination of closed vessels of small diameter, the examination of a 3-ft.-diam. tubular vessel with a welded dished end being well within the capacity of the unit.

Sulphur hexafluoride is used for both insulation and cooling of the X-ray tube, forced-circulation cooling of the anode being effected by means of an internal blower. The tank head



Portable X-ray unit

is of drawn aluminium with bolted dished ends and amongst the numerous protection devices fitted are shock-absorbent mountings for the tube in the tank head and further shock-absorbent mountings for the tank head in the cradle. A thermoswitch is fitted to guard against excessive temperature rises. **CPE 1624**

Temperature determination

Products which provide a way of determining industrial temperatures by means of a sharp, rapid, melting action are offered by J. M. Steel & Co. Ltd. These *Tempil* products are available in three forms.

The *Tempilstik* is a crayon which is smeared on to the object whose temperature is being measured; the smear obtained becomes liquid at its melting point. This indicates the temperature.

The *Tempil Pellet* is a tablet which is placed on the object, and at the first sign of melting the desired temperature has been reached.

Tempilaq is a liquid which is painted on the object and allowed to dry. When the required temperature is reached this mark liquefies sharply.

All three products are available in a wide range of temperatures from 113° to 2,000°F. and the pellet up to 2,500°F. **CPE 1625**

Fast-drying primer

Red lead primer which can be over-painted in 2 to 4 hr., as opposed to the usual 24 hr. or longer, is offered by John Williams & Co. Ltd.

The presence of moisture on steel structures normally prevents painting, particularly in winter. However, with the new primer, *Viternus V.P.* 51, painting under winter conditions is possible except in actual rainfall, snow or frost.

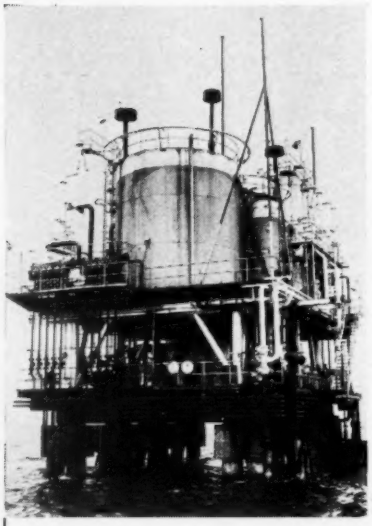
The primer contains an ingredient which has greater affinity for surfaces than moisture which is displaced and the paint, having superior adhesion, fastens itself and dries without harmful effect.

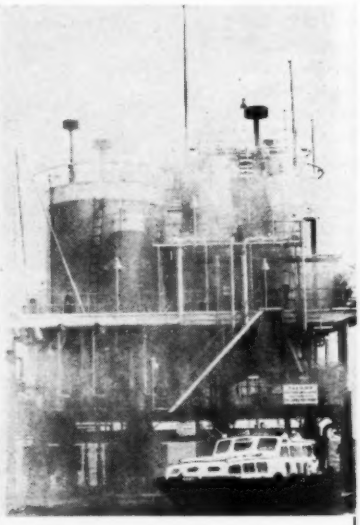
Because of its quick-drying properties, it eliminates the danger of contamination of the film from industrial fall-out. **CPE 1626**

Oxygen lancing

An unusual application of oxygen lancing solved a repair problem at the U.K.A.E.A.'s nuclear power station at Chapelcross recently when difficulty in removing a seized stud bolt in the casing of a main blower threatened a costly delay in bringing the reactor back on load. The damaged stud bolt, 10 in. long, $1\frac{1}{4}$ in. diam., and made of high-tensile steel, could not be removed from the main blower inlet flange. Until it was removed the blower could not be reassembled and this in turn delayed the restarting of the reactor and two turbo alternators after a maintenance shutdown.

Attempts to remove the bolt by drilling were unsuccessful and a cutting specialist from the British Oxygen Co. Ltd. was called in. He carried out the task using first a *Saffire* combined cutter with $\frac{1}{16}$-in. nozzle and then an oxygen lance fitted with a $\frac{1}{4}$-in. gas barrel. When the lancing operation was completed only slag remained in the pocket, which was removed by drilling to make way for the insertion of a new bolt. **CPE 1627**





Fire protection

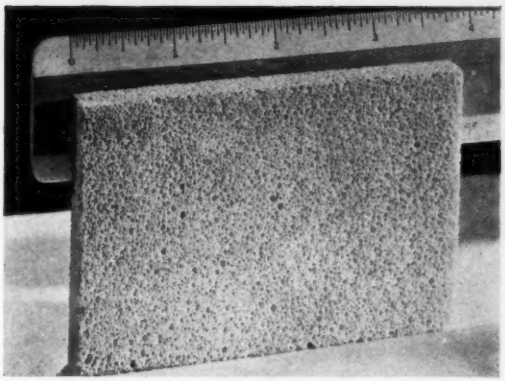
The picture on the right shows the *Fire-Fog* system of fire protection at the flow station of the San Jacinto Oil Co. on Venezuela's Lake Maracaibo under installation test. The station collects 50,000 bbl./day of crude oil from 20 wells beneath the 10-ft.-deep lake.

There are 146 *Fire-Fog* nozzles in strategic areas in the pipes and tanks, which are set off when the slightest fire is detected by the rate-of-rise heat-actuated devices throughout the station. These devices start off a flow of nitrogen gas from a nitrogen pressure cylinder. The gas is then propelled through an air motor starting a diesel engine which drives a 1,500-gal./min. vertical turbine fire pump at 100 p.s.i. pressure. This all takes place within seconds after the fire is detected. The system is made by the Automatic Sprinkler Corporation of Venezuela. **CPE 1628**

Remote control of valves

Valves which are said to be able to control most known fluids and gases up to temperatures of 100°C., because the valve body and clack material can be varied according to the line fluid, are the *Rayon-Patent* made by Meynell & Sons Ltd. The makers now offer remote-control mechanism—pressure closing/spring opening, pressure opening and closing, or pressure opening/spring closing.

The valves are said to be suitable for high-vacuum applications, and the design of the clack is such that, when the valve is closed, there is no pressure on the gasket and, as the rubber is moulded around and bonded to the spindle and pressure plate, there is no danger of it being pulled off and sealing the line. The upper part of the clack is so shaped that the moveable parts of the valve remain isolated from the line fluid completely eliminating the necessity of packing glands, and the full-bore characteristics reduce pressure loss to a minimum. **CPE 1629**



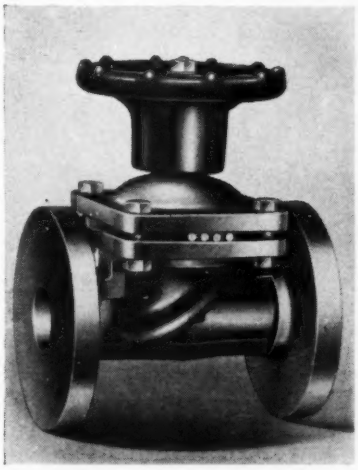
Ceramic insulating brick which withstands temperatures of 4,200° F.

Insulating brick

A ceramic insulating brick that withstands temperatures up to 4,200°F. is offered by Ipsen Industries Inc. It is in standard brick sizes of $2\frac{1}{2}$ in. × $4\frac{1}{2}$ in. × 9 in. It has a thermal conductivity at 2,200°F. of less than 1 B.T.U./sq.ft.hr.°F./in. and weighs about 2 lb./brick.

Basically it is a formulation of zirconium oxide material that is expanded and fired. A cellular structure consisting of uniform open pores with all cells interconnected permits gas to pass through for purging or evacuation. This porosity will also permit the passage of liquid. Its melting point is 4,620°F.

It has a temperature limit (hot face) of 4,200°F. in oxidising atmosphere, in nitrogen, and in hydrogen atmosphere. Other hot-face temperature limits include 4,200°F. under vacuum conditions, 3,000°F. in a reducing atmosphere with carbon present, 2,200°F. in contact with SiC and 3,000°F. in contact with SiO_2 or Al_2O_3. This material is readily cut, sawn or filed. **CPE 1630**



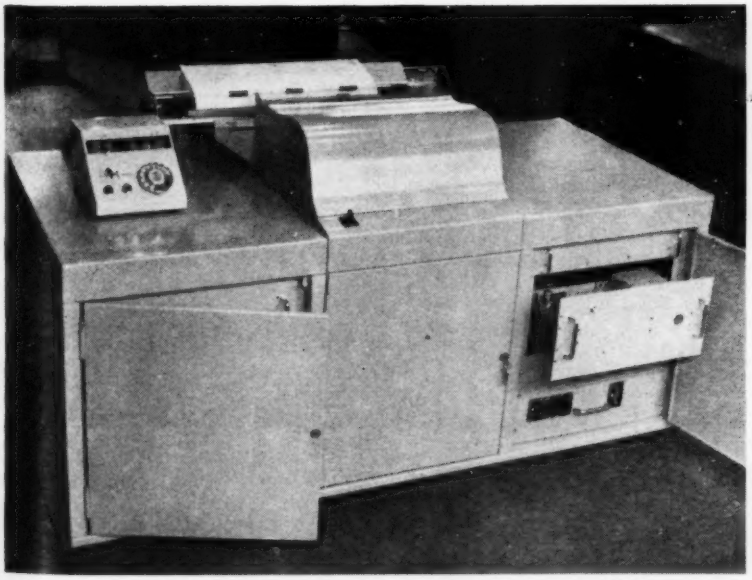
Valve operated by remote control

Data gathering

Bailey Meters & Controls Ltd. offer the *Digilog* information system, a means of gathering data and displaying them in numerical form. Essentially, it sequentially selects analogue signals, measures them and then converts them to digital form, suitable for printing on to a log sheet.

In addition to the automatic logging process, the system will give an alarm signal when important readings are departing from safe and efficient conditions. These readings are printed in red, in contrast to the normal black figure logging. It can also be adjusted to continuously scan all the inputs and only print out and alarm when an input signal deviates from pre-set limits.

Remotely sited channel monitors can be provided. This enables a supervisor to break in on a scan and, by dialling a particular input channel on a telephone-type dial, obtain the reading at that moment. The reading and channel identification is presented on a digital tube display unit and it can be arranged that the reading is corrected each time the *Digilog* scans the channel being monitored. **CPE 1631**



Print-out scanner which gathers data and displays it in numerical form

New Books

Radiation Chemistry of Organic Compounds. By A. J. Swallow. International Series of Monographs on Radiation Effects in Materials, Vol. 2. Pergamon Press, London, 1960. Pp. xiii + 380. 84s.

This is the second volume in a series under the general editorship of Prof. A. Charlesby, the first volume having been written by Charlesby himself on 'Atomic Radiation and Polymers'.

In this book Dr. Swallow has attempted to give an account of current knowledge relating to the effect of radiation on organic compounds. As explained in the preface to this volume, the growth of interest in radiation chemistry has increased 40-fold within the past 10 years, resulting in approximately 200 papers being published on this subject in 1957 alone. In writing this book all the original work published between 1895 and the middle of 1958, in English, French, German, Russian and Italian, has been surveyed, and the result is an excellent account of the subject to date.

The chapter headings are as follows:

General introduction
Experimental methods
Water and aqueous systems
Aliphatic compounds
Aromatic compounds
Polymers
Dyestuffs
Some substances of biological interest
Radiation chemistry and other fields

From these headings it will be seen that a wide field of interest has been covered. The first two chapters deal with the definitions used in radiation chemistry, the mechanism of the interaction of high-energy radiations with matter, the sources of radiation and the handling of samples.

In the third chapter the irradiation of water and aqueous systems, particularly the ferrous sulphate system, is discussed in detail. The chemistry of these systems will be of interest not only to radiation chemists but to physical chemists in general, for it involves the formation and effects of free radicals in these systems. The results applicable to water and aqueous systems are then extended to organic systems in general. Although not studied in such detail as water, the systems discussed by the author are well covered. Much is known about these systems—very much more remains to be done—and the author suggests at various points in the text lines of research that may prove fruitful.

In one respect a certain amount of duplication with Vol. 1 of the series has occurred—this is in the discussion relating to organic polymers. However, this duplication is unavoidable if the book is to be a comprehensive account. The scope of this book is such that it will be useful not only to the specialist wishing to have a ready reference to the current state of the subject but also to the general reader desiring to enlarge his knowledge of the various branches of chemistry. The fluent and descriptive manner in which it has been written makes it eminently readable.

F. G. R. GIMBLETT

Small Particle Statistics. By G. Herdan. Butterworth (revised and enlarged Second Edition). Pp. 418. 80s.

Workers in an ever-increasing number of branches of engineering and technology are coming to recognise the significance of variability in raw materials, in production and development methods and in final product, and to feel the need for a corresponding statistical technological outlook. There are such branches, unfortunately, where the practitioners—even when they do see the need for statistics—can only consult statisticians who are external to their mystery and are unfamiliar with its idiosyncrasies. What is desirable is a *fusion* of statistics with technology. This has been achieved in some fields, notably in production engineering, where statistical techniques are used as an integral part of the routine equipment, and where development (particularly in some branches of chemical engineering) is in some cases being led by men who are fully integrated statistical technologists.

The writing of a book such as 'Small Particle Statistics' represents a considerable step towards just such a fusion, this time with a topic which runs right across a number of fields, affecting metallurgy, mineral dressing, ceramics, gas analysis, dust analysis, paints, cement, soil engineering, plastics, petrology, etc. The author maintains that, in a large number of important processes of these and associated technologies, the particle size of the materials involved is an inherently statistical concept and that, consequently, statistical methods should be used in the problem of particle size determination, measurement and control. He gives what appears to be a comprehensive survey of the available methods, describing in detail the experimental procedures and their interpretation, producing a book which is a textbook or handbook of particle technology in which statistical ideas are used integrally, as and when appropriate. Some idea of the scope of the work may be gained from the five main sub-headings:

I. The determination of the fineness of solids.
II. The technological importance of the fineness of solids.
III. Attainment of a specified fineness and homogeneity in a substance.
IV. Principles of statistics of coarse disperse systems.
V. Experimental design and experimental errors of particle size determination, by M. L. Smith, W. H. Hardwick and P. Connor.

The author does not over-elaborate the statistical treatment; the concepts he needs are quite simple, basically the idea of a *distribution* (as in specifying the relative frequencies of different weights of particles in a powder), of *sampling* (the extent to which the composition of a relatively small quantity of the powder is liable to differ from that of the bulk which it represents) and of *significance tests* (criteria for estimating whether, *e.g.* two given samples may reasonably be regarded as representing the same bulk). These concepts are expounded and illustrated with a wealth of relevant data; indeed, it is an excellent feature of this book that real data, taken from the technical literature, is copiously used to illuminate the arguments.

Each chapter ends with a list of references, and at the end of the book is a list of 21 symposia and books on particle size analysis. The author index lists more than 500 names, and there is a detailed subject-index. The book is excellently printed and illustrated, and has very few misprints in the statistical sections (the only ones which the reviewer is competent to judge). The only ones noted were as follows:

Page 81, equation (6.15a). The right-hand member should have a further factor $1/x$.

Page 81, equation (6.16) and page

82, equation (6.16a). The limits of integration should be simply x_1 and x_2.

Page 157, line following equation (10.4a). For b_{xy} read b_{yx}.

E. H. LLOYD

Chemical Processing Nomograph. Editor: D. S. Davis. Chemical Publishing Co., 1960, 212 Fifth Avenue, New York. Pp. 255.

Prof. Davis is dedicated to the cause of alleviation of the engineer's burden of mental processes by the use of silent straight edges and peaceful pieces of paper. On his pieces of paper are labour-saving labelled lines ingeniously disposed and subtly subdivided to convey at the wave of the wand solutions to such problems as that of finding h from the relationship:

$$h = 0.023 \frac{G^{0.8}}{D^{0.2}} \quad \frac{C_p{}^{0.4} k^{0.6}}{\mu^{0.4}}$$

once numerical values of the five literal symbols are known. In this rather complex, if well known, example of the art, there are of course, six graduated scales and three ungraduated reference lines provided, and the value of h is obtained after four simple operations.

Prof. Davis evidently has a large number of ardent disciples and one has only to experience the light touch and the enthusiasm of the exposition in Unit 1 (*i.e.* chapter 1) to understand why this is so. Those Britishers who possess no television sets may find the American idiom and allusions obscure. Nigh on 50 contributors are cited in connection with the 166 charts provided in the book. Their contributions are arranged in 15 units as follows:

(1) General procedure
(2) Heat (flow)
(3) Fluid flow
(4) Pulp mill calculations
(5) Vapour pressure
(6) *P, V, T* relationships
(7) Solubilities
(8) Densities and specific gravities
(9) Viscosities
(10) Relative humidity
(11) Costing
(12) Sizing of equipment
(13) Conversion
(14) Standard deviation and quadratic equations
(15) Miscellaneous

Chart 15—10, 'Calculating Effect of Conditions on Free Energy of Gaseous Reactions' will cause the raising of some thermodynamic eyebrows. As explained in the preface, these charts have already appeared in print in other places. If there be any Britishers who are obliged to purchase such books out of their private purse they will certainly baulk at paying £4 10s. or $12 (U.S.). Those who are sufficiently refined (or old-fashioned) to regard the reporting of straightforward calculations to an accuracy of 0.1% or even 1.0% of the figure obtained as a matter of honour, will feel constrained to reconstruct many of the charts on a scale four times their published size (6 in. × 9 in.). They will also wish to have the sheets separate from one another so that they may be used flat and free from obstruction. A note as to the degree of isotropy of the paper in the plane of the sheet would also relieve anxiety as to whether the nomographs need to be kept in a humidity and temperature-controlled room. (This is probably taken for granted in the U.S.).

The main reference to the basic work on the theory underlying the construction of nomographic charts is, not unnaturally, to a Rheinhold publication (1955), 'Nomography and Empirical Equations'. In this connection a small, neat and penetrating exposition entitled 'The Construction of Nomographic Charts', by F. I. Mavis, International Text Book Co., Pa., U.S. (1939), has been found useful by your reviewer.

K. L. BUTCHER

A History of Platinum, from the Earliest Times to the 1880s. By Donald McDonald. Johnson, Matthey & Co. Ltd., 1960. Pp. 254. 35s. net.

The price we have to pay for insisting upon an ever-higher degree of specialisation from our scientists and engineers is an inevitable narrowing in their outlook. The specialist sooner or later loses interest in the wider implications and the historical roots of science and technology. In the long run this produces a sterile, anti-scientific spirit which runs counter to the broad humanistic outlook of scientists in previous generations. The author is therefore to be congratulated on having produced a history of platinum, a subject of little immediate interest to most chemists and chemical engineers but one that brings us into contact with the chemical giants of the past two centuries.

Although platinum was already used by the Egyptians, until the present century the only form in which it was available to commerce was in the form of water-borne grains containing 50 to 80% platinum, the remainder consisting of ruthenium, rhodium, palladium, osmium and irridium and a certain amount of copper and gold. Platinum was never recognised as a separate metal by the Ancients and it was not until the Spanish conquistadores searched the New World for gold that extensive platinum deposits were discovered in Colombia in the early 18th century. Originally this new metal was considered a worthless nuisance since it demanded a great deal of labour to remove it from gold; the Spaniards gave it the name *platina*, a somewhat derogative diminutive of *plata*, meaning silver!

Mr. McDonald traces the development of platinum science and technology from the early 18th to the late 19th century. One of the leading roles in this story was played by Wollaston, who discovered palladium as a metal separate from platinum, by dissolving crude platinum in aqua regia and examining the solution after precipitating with sal ammoniac. The use of platinum boilers for the concentration of sulphuric acid was its first industrial application which Deville and Wollaston developed and exploited.

Naturally Johnson, Matthey & Co. have played a leading role in the history of platinum, and the author, a former managing director of the company, describes the early years of this firm and its influence on the platinum industry. The story finishes in 1880—after this period the study of platinum was removed from the realm of the esoteric scientist to the platinum manufacturer's laboratory.

Not only is this book scientifically exciting but also well written and produced. The many references cited at the end of each chapter are proof of the extensive literary research which Mr. McDonald must have undertaken. As a history of one branch of technology, this is a model example. Every scientist and engineer, whether he has connections with platinum or not, would be well advised to have this book on his shelf and from time to time refer to the many interesting scientific developments contained in it.

I.L.H.

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Nuclear Notes

Reactor for outer space

A prototype of the first nuclear reactor for outer space has completed operational ground tests.

It was developed by Atomics International as part of the U.S. Atomic Energy Commission's Systems for Nuclear Auxiliary Power programme (SNAP).

The high-temperature test reactor weighs about 250 lb. and is fueled with enriched uranium. It will generate auxiliary electric power in the kilowatt range continuously for a year.

The system will use a thermoelectric converter to produce up to one or two kilowatts of electricity from reactor heat. Miniature turbine generators will be used to produce electricity.

The experimental reactor produces 50 kW of heat at a coolant outlet temperature of 1,200°F. It has operated for more hours at this temperature than any other reactor in the world. A continuous 1,000 hr. test run was achieved.

Nuclear filters

The filters in use at the U.S. Atomic Energy Commission's atomic plant at Hanford are said to trap 99.95% of the radioactive matter created by the plutonium process.

The space filters are an outgrowth of research done before and during the second world war aimed at developing filter media from a variety of fibrous materials for use in gas masks and in ventilation air systems.

Filters are used individually in laboratory hoods, or in large banks able to clean many thousands of cu.ft./min. Made of glass-fibre paper consisting of tiny fibres about 1/28,000 in. diam., a single filter unit purifies 1,000 cu.ft./min. of air.

The filters are constructed of fire-resistant materials to prevent the possibility of one catching fire and spreading potentially harmful radioactive material.

Radioactive wastes

Radioactive wastes arise mainly in nuclear industry. The largest amount comes from the chemical treatment of uranium after it has been used as fuel in atomic reactors. Other wastes are produced during mining, treatment and refinement of radioactive ore, the operation of reactors and the production and use of radioisotopes. Different wastes contain very different concentrations of radioactivity. Throughout the world the practice has been to contain and store all highly concentrated wastes in heavily shielded containers. Wastes with lesser concentrations are sometimes diluted and released to the environment.

An international panel of experts was convened recently by the Director-General of the International Atomic Energy Agency to consider the subject of radioactive waste disposal into fresh water.

Spain in C.E.R.N.

Last month Spain became the 14th member state of C.E.R.N., the European Organisation for Nuclear Research.

Assession of Spain was unanimously decided by the delegates of the 13 actual member states, namely Austria, Belgium, Denmark, France, the German Federal Republic, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, the U.K., and Yugoslavia. The delegates were in Meyrin for the 18th session of C.E.R.N.'s council.

Observers for Spain at the council were Mr. Jose-Manuel Aniel-Quiroga, permanent delegate of Spain in Geneva, Mr. Carlos Sanchez del Rio, chief of the division of physics and reactors Junta de Energia Nuclear, Madrid, and Mr. Pedro Temboury, a member of the permanent delegation of Spain in Geneva.

Trade Unions and nuclear energy

The implications for the workers of the increasing use of nuclear energy for peaceful purposes were discussed in Düsseldorf recently by 60 Trade Union experts, representing 30 national Trade Union federations in 16 European countries, the U.S. and Canada. The seminar was organised by the O.E.E.C. European Productivity Agency and in collaboration with the Federal German Productivity Centre and the German Trade Union Federation.

Delegates expressed concern at the danger to workers from overdoses of radiation and demanded that Union representatives should be brought in at every stage, both in the design of plant and in the day-to-day handling of radioactive sources. It was recognised, however, that too few Union representatives knew enough about the subject, and several delegates resolved to see what could be done in their countries to train Trade Union organisers to inspect industrial and agricultural undertakings.

Both Dr. H. Jammet of Saclay and Dr. G. Fredrichs of the Industrie Gewerkschaft Metall explained that the dangers could be exaggerated, while Mr. G. Taylor of the American Federation of Labour and Mr. F. Hayday of the National Union of General and Municipal Workers said that they had found on the whole that existing safety regulations were adequate in themselves and were being properly applied.

The question of whether nuclear energy is likely to cause unemployment was discussed. Dr. Hardung-Hardung of E.N.E.A. said that though nuclear-generated power would probably become competitive in price with traditional sources sometime between 1965 and 1970, given the growing needs of the world for energy, with special reference to underdeveloped countries lacking mineral resources, there would probably be a demand for all forms for many years to come.

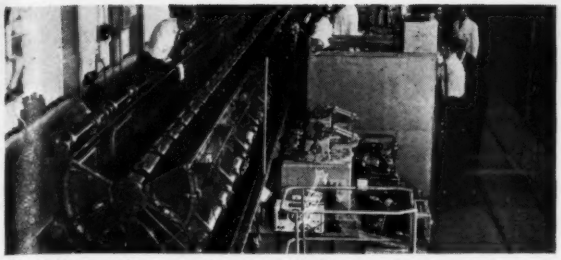
There was a general demand for further Trade Union conferences on the subject, each conference confined to one particular facet of the problem.

Japanese research reactor

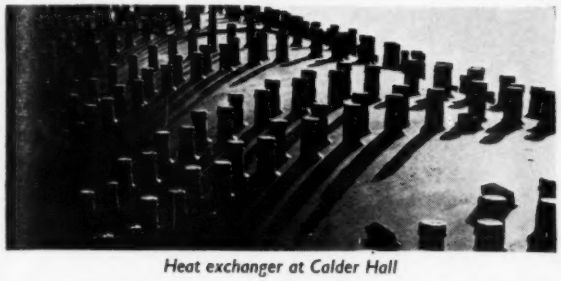
General Electric Japan Ltd. has been awarded a contract by the Japan Atomic Energy Research Institute to construct a 12,500-kW demonstration nuclear power plant in Japan.

The plant will be used for nuclear research and development as well as power production. It will be at Tokai Mura, about 50 miles north-east of Tokyo, in a nuclear development centre which now includes several research reactors. Scheduled to achieve its initial chain reaction early in 1963 the plant is expected to generate the first nuclear electric power in the Far East.

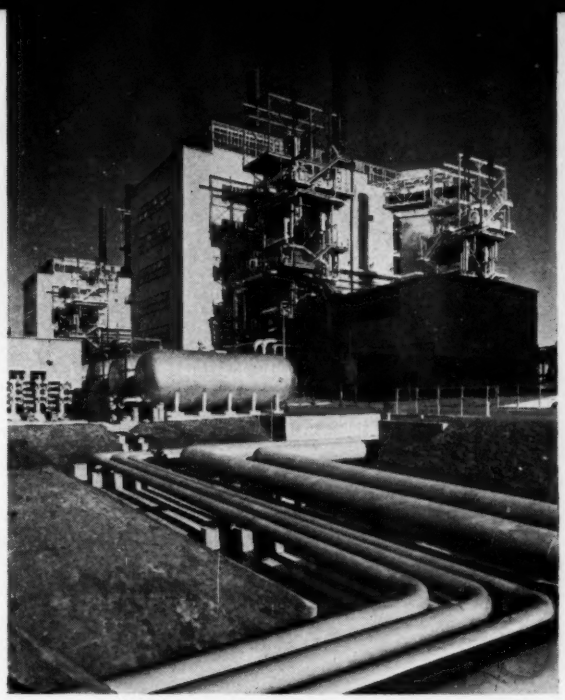
The reactor will be a direct-cycle boiling-water type with natural circulation cooling. The fuel will be enriched uranium.



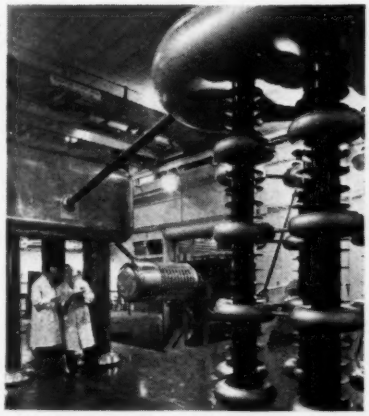
50 MeV proton linear accelerator at the National Institute for Research in Nuclear Science



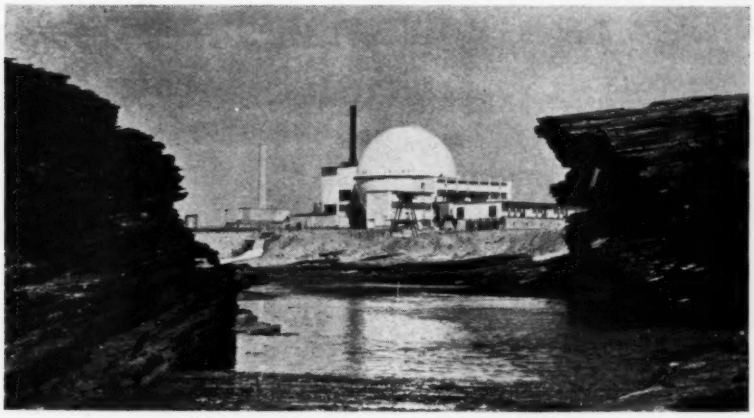
Heat exchanger at Calder Hall



Chapelcross nuclear power station in Scotland



The Cockcroft-Walton high-voltage generator



Experimental fast fission breeder reactor at Dounreay

The tandem electrostatic accelerator at A.W.R.E., Aldermaston

Atom in Camera

The photographs on this page are part of the exhibition staged by Ilford Ltd., with the co-operation of the U.K.A.E.A., at Ilford House, London. It was opened by Sir Roger Makins, chairman of the Authority.

It is the first London photographic exhibition to be devoted entirely to the peaceful uses of atomic energy.

The technique of telling the atomic story in pictures is expected to have a strong appeal to young people, particularly those contemplating a scientific career.

In his opening speech Sir Roger said that he believed that the fear and prejudice about nuclear energy were diminishing in the U.K.

CPE World News

UNITED STATES

Phosphoric acid plant

A $1,500,000 plant to manufacture phosphoric acid, used in the production of high-analysis fertiliser, will be built by Olin Mathieson Chemical Corporation at Joliet, Ill.

The capacity of the plant will be about 50,000 tons p.a. The phosphoric acid will be a 75% concentrate.

Preliminary work is under way and the plant should be completed by the end of April 1961.

This was the third new chemical plant to be started by the corporation in 1960. Construction is under way on a hydrazine plant in Saltville, Va., to supply fuel for the *Titan II* missile, and on a chlorine and caustic soda plant in Charleston, Tenn.

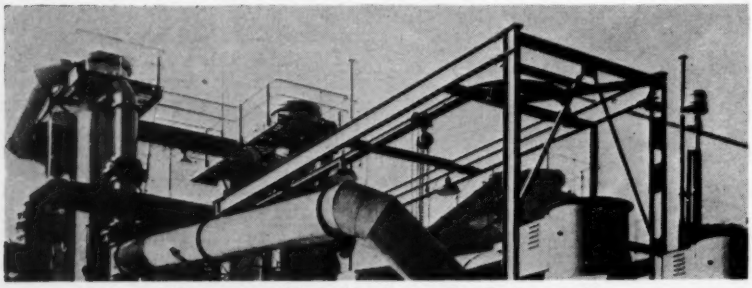
AUSTRALIA

Treating town gas

The dehydration of town gas before distribution has been practised for many years in Australia. A number of gasworks have utilised calcium chloride as the drying agent, but plant of this type has certain disadvantages, therefore a good case can be made for reducing the dewpoint of the gas by direct contact with refrigerated water.

A disadvantage of this system is that the chilled water is an intermediary between the ammonia in the refrigerator evaporator and the gas, resulting in greater cost of the plant, higher running costs and additional thermal losses. This can, however, be minimised if the gas is cooled by direct contact with the coils of the refrigerator evaporator.

The first plant of this type to be installed in Australia was started up at the East Perth gasworks, which is operated by the State Electricity Commission of Western Australia. This plant, which was designed by Woodall-Duckham, Australia, in conjunction with W. C. Holmes & Co. Ltd. and Gordon Bros. Ltd., Australia, handles two independent low-pressure gas streams, each of 4 million cu.ft. day. During the summer, gas may enter the plant at 100°F. saturated, whilst at other times of the year the gas temperature is about 70°F.



Refrigerant gas dehydration plants at East Perth gasworks

ALGERIA

Detergent and cosmetics

Unilever is to build a £900,000 detergent and cosmetic plant on the outskirts of Algiers. Output of detergents is expected to increase from 10,000 tons p.a. to 20,000 p.a. by 1965. Phosphate deposits at Djebel Onk are to be exploited by a new company. the Société du Djebel Onk. A concentrating plant with an annual capacity of 800,000 tons is to be set up nearby. Open-cast operations, which are to start in 1962, will more than double the country's phosphate output (531,000 tons in 1959).

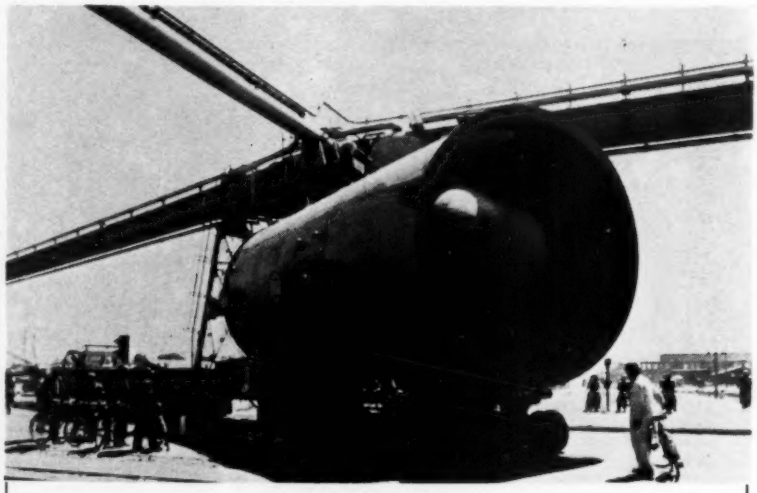
GERMANY

Explosion in Ruhr

Some 13 people were killed and 15 seriously injured in an explosion last month at an oxygen plant at the Westfalen Hutte at Dortmund

The plant, which belongs to the Knapsack-Griesheim chemical works of Cologne, supplies the Westfalen Hutte steelworks and other mills in Dortmund with liquid oxygen, produced under high pressure.

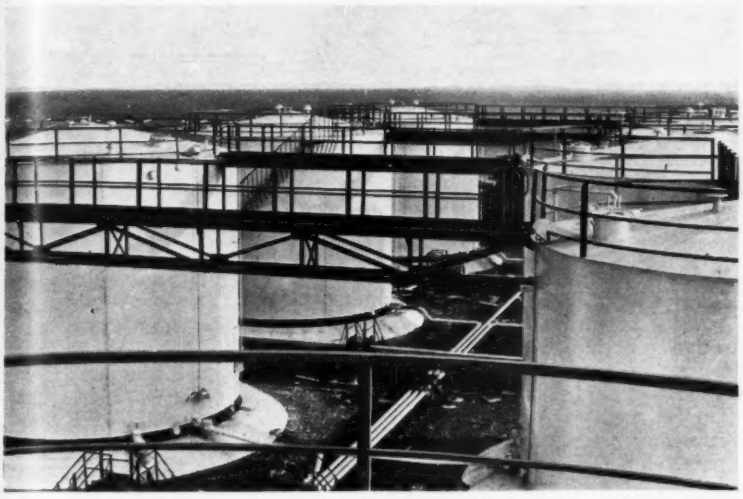
The explosion is thought to have occurred while the oxygen was being drawn off into containers. A short time before, the plant engineer had been called to examine some damage to the stills. The pipe carrying waste gases away from the plant, and running just outside the scene of the explosion, remained undamaged.



NETHERLANDS

A carbon monoxide converter being taken from the North Sea Canal to the site of the gas reform plant at Ijmuiden being built for Mekog by Chemical Construction Ltd.

CPE Company News



Some of the vertical light oil storage tanks in the new depot on the same site as the fuel oil terminal

Welsh oil terminal

A new fuel oil terminal of the Regent Oil Co. Ltd. at Queen Alexandra Dock, Cardiff, was opened recently by the Lord Mayor of Cardiff, Alderman Mrs. Dorothy Lewis, O.B.E.

Costing £500,000 and built in under a year, it will fulfil the dual function of providing the company with ocean storage in South Wales for fuel oils and of replacing their present light oil depot at Penarth by a modern installation with increased storage capacity and improved distribution facilities.

Plasticiser alcohol expansion

The heavy organic chemicals division of I.C.I. Ltd. is to increase its capacity for the manufacture of alcohols by the carbonylation of olefinic feedstocks. A fourth unit, with a capacity of 30,000 tons/yr. of plasticiser alcohols, is to be erected at Billingham, Co. Durham.

This extension is planned not only to meet the requirements of the rapidly expanding U.K. plasticiser industry but also to enable the company to supply the increasing demands of overseas customers.

Plant manufacturer bought

The business of George Royston & Son. Ltd. of Barnsley has been acquired by Newton Chambers & Co. Ltd.

Royston's design and manufacture chemical plant and equipment fabricated in mild steel, stainless steel, aluminium and special alloys. They specialise in sulphate of ammonia plants for the manufacture of Grade A sulphate.

Their activities will fit effectively into the expanding pattern of the engineering division of Newton Chambers. Mr. K. E. Walker, director in charge of the division, will be chairman of the company, and Mr. D. B. Royston will continue as managing director.

New gasworks

A new gasworks is to be built in Norwich for the Eastern Gas Board.

The works will rely entirely on cyclic catalytic reforming plant for gas production and will normally gasify light distillate. The plant will include two MS 33 units and will have an initial capacity of 3.2 million cu. ft. of 500 B.T.U. gas after enrichment with liquefied petroleum gases. The plant will be built by Woodall-Duckham Construction Co. Ltd. and is scheduled to be in operation before the end of this year.

A plant of similar design, which will also gasify light distillate and produce 2 million cu.ft./day of gas, is now under construction at the Cambridge works of the Eastern Gas Board and will be put into operation in the early part of this year.

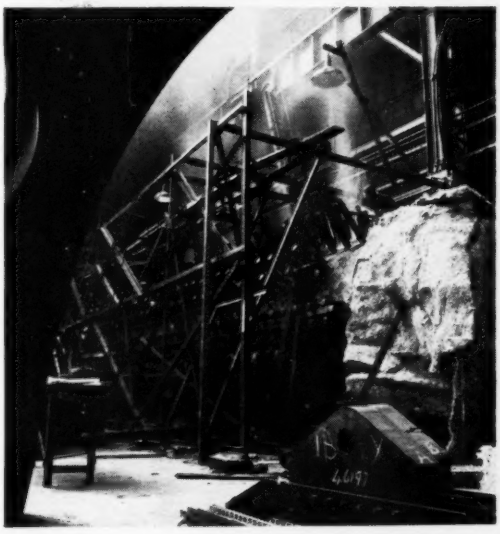
Equipment for power station

In modern, high-duty, water-tube boiler construction it is now the practice for the boiler tubes to be welded to short stubs which form an integral part of the boiler drums.

Four drums of this design have recently been completed in the works of G. A. Harvey & Co. (London) Ltd. to the order of Mitchell Engineering Ltd., for the Electricity Supply Commission of the Union of South Africa at their new Komati power station in the Transvaal.

The drums are for two steam generating units, each rated at 900,000 lb. steam/hr. but capable of 990,000 lb./hr. at peak load.

The drums are designed for a steam pressure of 1,500 p.s.i. at a temperature of 590°F.



Welding-in process of the stub tubes to a main steam drum

CPE Diary

FEBRUARY 14 TO 17 Symposium on **light metal industry in India** to be held at Jamshedpur. Details from National Metallurgical Laboratory, Jamshedpur 7, India.

FEBRUARY 15 Lecture on **science and the developing countries** by Prof. Blackett at the Geological Society, Burlington House, London, W.1. Details from the Institution of Chemical Engineers, 16 Belgrave Square, London, S.W.1.

FEBRUARY 20 Lecture on **controlled fusion reactions** by Prof. Blackett organised by the Institution of Mechanical Engineers, 1 Birdcage Walk, London, S.W.1.

FEBRUARY 20 Meeting of the nuclear energy group of the Institution of Mechanical Engineers on the **influence of availability of enrichment on reactor type and design.** Details from the Institution, 1 Birdcage Walk, London, S.W.1.

FEBRUARY 23 Lecture by Prof. W. Hume-Rothery on the **theory of the alloys of copper** to be held at the Royal Institution, Albemarle Street, London, W.1. Details from the Metal Physics Committee of the Institute of Metals, 17 Belgrave Square, London, S.W.1.

FEBRUARY 23 All-day symposium on **terpene chemistry** arranged by Prof. A. W. Johnson at the Imperial College, London, S.W.7. Details from the Chemical Society, Burlington House, Piccadilly, London, W.1.

MARCH 1 TO 2 Symposium on **user experience of large-scale industrial vacuum plant** to be held in London. Details from the organisers, the Institution of Mechanical Engineers, 1 Birdcage Walk, London, S.W.1.

MARCH 5 TO 6 Practical course in **radiochemistry** to be held in the Liverpool College of Technology. Details from J. W. Lucas, College of Technology, Byrom Street, Liverpool 3.

MARCH 6-9 Thirteenth **Oil and Colour Chemists' Association Exhibition** to be held in the Royal Horticultural Society's New Hall, London, S.W.1.

MARCH 7 Papers on **fluidisation** from A.E.R.E. Harwell at the Geological Society, Burlington House, London, at 4 p.m. Organised by the Institution of Chemical Engineers, 16 Belgrave Square, London, S.W.1.

MARCH 7 First in a series of conferences organised by the British Institute of Management on **management in the sixties** to be held in the Connaught Rooms, London, W.C.2. Mr. William H. Whyte, author of the 'Organisation Man', is coming from the United States for this conference. Details from the B.I.M., Management House, 80 Fetter Lane, London, E.C.4.

MARCH 16 Lecture on **charge transfer in organic solids induced by light** to be given by Prof. A. N. Terenin in the rooms of the Chemical Society, Burlington House, London, W.1.

MARCH 21 Discussion meeting of the Institution of Chemical Engineers on **some factors in the safe operation of air separation plants** at the Geological Society, Burlington House, London, W.1, at 5.30 p.m. Details from the Institution of Chemical Engineers, 16 Belgrave Square, London, S.W.1.

APRIL 11 A joint meeting of the Society of Chemical Industry and the Institution of Chemical Engineers on a systematic classification of chemical processes and equipment to be held at the Society of Chemical Industry, 14 Belgrave Square, London, S.W.1, at 6 p.m.

£ s d

CHEMICAL PLANT COSTS

Cost indices for the month of December 1960 are as follows:

Plant Construction Index: 181.2

Equipment Cost Index: 169.9

(June 1949 = 100)

£ s d

Correspondence

Flow measurement

SIR,

Your readers may like to know that a new edition of British Standard 1042 (code of flow measurement) will be published shortly. Reference to this standard was made in the article 'The Control of the Flow of Fluids', by K. L. Butcher, in your December 1960 issue. The revised code he mentions was an early draft of the proposed revision of B.S. 1042 and should not be taken as in any way definite.

C. DOUGLAS WOODWARD
Press and Public Relations Officer,
British Standards Institution,
Park Street,
London, W.1.

Barcelona Congress

SIR,

I have read your article about the 32nd International Congress of Industrial Chemistry (CHEMICAL AND PROCESS ENGINEERING, Dec. 1960, **41** (12), 553) and I want to thank you for including my name and realising how terrible my job was at the Congress.

I agree with you about the low standard of most of the papers presented, but I cannot agree that the communications with a 'sales bias' were the prevalent tendency. Regarding the excessive number of sections, there were many more sections in all congresses organised previously by the Société de Chimie Industrielle. We cut as much as we could.

The difficulty of language was an insoluble problem, since simultaneous translations were too expensive. Anyway, most of the Spanish chemists are able to speak one or two foreign languages and they could answer any questions. I myself presented my paper, 'An Acetylenic Approach to Patulin Derivatives', in English to make it more understandable to everybody.

FELIX SERRATOSA
Catedra de Quimica Organica,
University of Barcelona.

Gas chromatography. A brochure describing the *Vapor Fractometer*, a new gas chromatography instrument incorporating high-resolution Golay columns and sensitive detectors, has been published by the instrument division of the Perkin-Elmer Corp.